SEDIMENTOLOGY, ICHNOLOGY AND SEQUENCE STRATIGRAPHY OF THE LOWER CAMBRIAN GOG GROUP, SOUTHERN ROCKY MOUNTAINS, CANADA

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By

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ABSTRACT

The architecture, distribution and facies of sandstone bodies in the Gog Group of the southern Rocky Mountains of western Canada record the dynamics of sand movement on the broad continental shelf of West Laurentia during the Early Cambrian phase of worldwide transgression. This study focuses on the stratigraphy, sedimentology and ichnology in the Bow Valley region, specifically the sector from Mount Assiniboine northwest to the North Saskatchewan River. The objectives of this project were several-fold: (1) revise the existing stratigraphic nomenclature; (2) document the sedimentary facies; (3) identify facies assemblages and interpret them in terms of sedimentary processes and environments; (4) characterize sandstone body geometries; (5) develop a sequence-stratigraphic framework; (6) document trace-fossil occurrences; and (7) characterize different trace-fossil assemblages in terms of colonization trends and prevailing paleoenvironmental conditions.

The Gog Group in this area has historically comprised four units, the Fort Mountain, Lake Louise, St. Piran and Peyto formations. North of Bow Pass an additional unit, the Jasper Formation, occurs below the Fort Mountain Formation and is related to accommodation created by active rift-faulting during the latest Neoproterozoic. In the Lake Louise and Lake O'Hara area, four new formal subdivisions within the St. Piran Formation are proposed: Lake O'Hara, Lake Oesa, Lake Moraine and Wiwaxy Peaks members.

The sequence stratigraphy of tide-dominated setting has yet not been fully explored. The stratal architecture of the Lake O'Hara and Lake Oesa members reveals a new mechanism for the formation of the regressive surface of marine erosion landward of the lever point of balance between sedimentation and erosion in the subtidal environment. As the shoreline is forced to regress with falling sea level, the laterally continuous tidal flats advance and the preexisting shallow-subtidal compound dunes are scoured by strong tidal currents that carve gradually a new equilibrium profile. We argue that the accretion of intertidal flats on top of subtidal sands is an overlooked yet predictable component of falling-stage systems tracts in tide-dominated settings.

The Gog Group also offers an opportunity to explore animal–sediment relationships in a high-energy setting, during the early phase of Phanerozoic diversification. The presence of constrasting ichnofabrics within a single Early Cambrian sand-sheet complex illuminates how the colonisation trends of suspension and detritus feeders were controlled by factors specific to the various subenvironments.

The variety of sandbody types in the Gog Group reflects varying sediment supply and location on the inner continental shelf. Five types of compound cross-stratified sandstone are distinguished based on foreset geometry, sedimentary structures and internal heterogeneity. These represent five broad categories of subtidal sandbodies: (1) compound-dune fields; (2) sand sheets; (3) sand ridges; and (4) patchy dunes. Trace-fossil distribution in these tide-dominated sand bodies and adjacent sediments is mostly controlled by an interplay of substrate mobility, grain size, turbidity, water-column productivity, and sediment organic matter. Salinity is a critical factor in marginal-marine locations but played no role in this region of the shelf.

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Dedication

To my friend “el chileno” Martín Rodríguez†. I will always be thankful for his guidance.

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CHAPTER 1

Introduction

INTRODUCTION

Shallow-marine sandstone of the Gog Group in the southern Rocky Mountains comprise part of the vast terrace of siliciclastic deposits that rimmed the continental margin of western Canada, indeed almost contiguously around Early Cambrian Laurentia. It lies at the base of one of the thickest Cambrian sections in the world and records the initial phases of the early Paleozoic transgression onto the craton. Seemingly monotonous, and perhaps for this reason it has escaped detailed study, the Gog Group is revealed to consist of a more varied lithology than hitherto appreciated.

Continuous sedimentary successions without major interruptions provide an instructive opportunity to trace depositional evolution of the broad shelf setting in this region. Moreover, in these sedimentary rocks the Cambrian explosion of life is recorded in the form of body and trace fossils, including the soft-bodied fauna of the Burgess shale.

Lithologic variations, sedimentary structures and trace fossils in the Gog Group have been previously documented at reconnaissance level. However, an integrative study including sedimentologic, ichnologic and sequence-stratigraphic information had not yet been attempted.

The objectives of this project were several-fold: (1) revise the existing stratigraphic nomenclature; (2) document the sedimentary facies; (3) identify facies assemblages and interpret them in terms of sedimentary processes and environments; (4) characterize sandstone body geometries; (5) develop a sequence-stratigraphic framework; (6) document trace-fossil occurrences; and (7) characterize different trace-fossil assemblages in terms of colonization trends and prevailing paleoenvironmental conditions.

Theses structure

This is a paper-based thesis. Thus each of the four chapters corresponds to a manuscript submitted or prepared for a peer-reviewed journal. Chapter 1 focuses on lithostratigraphic aspects, including a general description and interpretation of lithofacies for the whole unit. This manuscript has been accepted for publication in the *Bulletin of Canadian Petroleum Geology*. Chapter 2 deals with sequence stratigraphy, and expands the implications on a newly detected unconformity within the St. Piran Formation in the understanding of tide-dominated forced-regressive systems. This is under review in *Geology*. In chapter 3, ichnologic aspects of the Gog Group are addressed, especially pipe-rock ichnofabric. This manuscript is in press in *Lethaia*. Chapter 4 focuses on compound cross-stratification variability in the Gog Group, and elaborates on the major types of shelf sandbodies and their deposits. This manuscript will be eventually submitted to *Sedimentology*.

Achievements

Through this thesis, the Gog Group is now described in detail. Through the revision of its lithostratigraphy, new members are now established, allowing future detailed studies to be placed in a better nomenclatural context. Forced-regressive tidal flats are described for the first time from the rock record. The response of tide-dominated coastlines to a forced regression is now better understood, and this expands the implication of falling-stage systems tracts. The study of pipe-rock ichnofabrics allowed me to characterize early mixground ecosystems and ascertain paleoecologic controls in sand-sheet complexes.

Finally, the study of compound cross-stratified sandstone variability in an environmental context has permited a more complete classification of subtidal sandbodies.

I believe that by studying the Gog Group I have “awakened a giant” as it were, and these rock will play a major role in our understanding of tide-dominated shallow-marine systems.

CHAPTER 2

The daunting Gog

Stratigraphy and sedimentary environments of the Lower Cambrian Gog Group in the southern Rocky Mountains of western Canada: Transgressive sandstones on a broad continental margin

ABSTRACT

The architecture, distribution and facies of sandstone bodies in the Gog Group of the southern Rocky Mountains of western Canada record the dynamics of sand movement on the broad continental shelf of West Laurentia during the Early Cambrian phase of worldwide transgression. These sandstones represent early deposits of a passive margin under high rates of sediment supply; accommodation was sustained by high rates of thermal subsidence plus sea-level rise. This study focuses on the stratigraphy and sedimentology in the Bow Valley region, specifically the sector from Mount Assiniboine northwest to the North Saskatchewan River. The objectives are to: (1) revise the existing stratigraphic nomenclature; (2) provide a general facies description and paleoenvironmental analysis of the constituent units; and (3) place the depositional setting in the context of the evolution of the Western Canada Sedimentary Basin.

The Gog Group in this area has historically comprised four units, the Fort Mountain, Lake Louise, St. Piran and Peyto formations. North of Bow Pass an additional unit, the Jasper Formation, occurs below the Fort Mountain Formation and is related to accommodation created by active rift-faulting during the latest Neoproterozoic. In the Lake Louise and Lake O’Hara area, four new formal subdivisions within the St. Piran

Formation are proposed: Lake O’Hara, Lake Oesa, Lake Moraine and Wiwaxy Peaks members.

A wide range of subenvironments is recognized. The Fort Mountain Formation and the uppermost part the Lake O’Hara and Moraine Lake members record shallow-subtidal sedimentation. The correlative interval at Mount Assiniboine appears to have been deposited closer to the source area, and paleocurrents reveal sediment transport towards the north, parallel to the shoreline. The Lake Louise Formation was deposited in a protected low-energy, inner-shelf setting, while most of the Lake O’Hara Member records inner-shelf compound dunes and sand sheets. The Lake Oesa Member, which erosively overlies the Lake O’Hara member, represents deposition in a tidal-flat environment. It is capped by a transgressive shoreface consisting of the lowermost deposits of the Moraine Lake Member. A record of sedimentation in inner-shelf conditions dominates the middle part of this unit, but with facies indicative of deposition in shallow subtidal conditions in the upper part. The Wiwaxy Peaks Member represents an inner-shelf sand-ridge complex, followed by development of a shoreface environment. The overlying limestone-dominated Peyto Formation records deposition on a carbonate ramp related to a decrease in siliciclastic sediment supply.

Introduction

Shallow-marine sandstones of the Gog Group in the southern Rocky Mountains are part of the vast terrace of siliciclastic deposits that rimmed the ancient continental margin of western Canada and much of early Cambrian Laurentia. The Gog Group lies at base of one of the thickest Cambrian sections in the world (Aitken, 1997) and records the initial phases of early Paleozoic transgression. Dominant paleocurrents flowed towards the west, carrying sediments derived from the Canadian Shield and its extension beneath the western plains (Mountjoy and Aitken, 1963).

Correlative Early Cambrian sandstones mantling the margins of Laurentia include the Backbone Ranges Formation in the Mackenzie Mountains (MacNaughton et al., 1997), Bradore Formation in southern Labrador (Long and Yip, 2009), Zabriskie Quartzite in Death Valley (Prave, 1991), Chillowee Group in Virginia (Simpson and Erikson, 1990; Simpson, 1991), Hardyston Formation in Pennsylvania (Simpson et al., 2002), Mt. Simon Formation in Wisconsin (Driese et al., 1980), and Eriboll Formation in Scotland (McKie, 1990), the last being part of a crustal fragment of East Laurentia (e.g. Cawood et al., 2007). These units were deposited during the breakup of Rodinia and accompanying global transgression. Land plants were virtually absent before the Silurian, which favoured development of extensive subaerial dune fields and braided fluvial systems on land (Dalrymple et al., 1985; MacNaughton et al., 1997; Rainbird et al., 1997; Davies and Gibling, 2010). However, microbial mats may have stabilized sediment on land, allowing intense weathering to produce mature quartz arenites (Dott, 2003). Large amounts of sediment were carried from the continent to the shelf by fluvial systems or reworked by the flooding of pre-existing sandy coastal deposits during transgressions (Simpson and Eriksson, 1990), with the result that these were the sandiest seas of the Phanerozoic.

Continuous sedimentary successions that apparently lack major faults provide an opportunity to trace the tectonic and sedimentologic evolution of West Laurentia. The architecture, distribution, facies and ichnology of sandstone bodies provide important clues towards a better understanding of sand dynamics on the broad, transgressive continental shelf. Our study deals with the stratigraphy of the Gog Group in the sector from the type area at Mount Assiniboine north to Mount Chephren near the North Saskatchewan River (Fig. 1). Outcrops along the Bow Valley belong to two parallel thrust sheets separated by the Simpson Pass fault, for which palinspastic restoration at Lake Louise suggests a shortening of some 12 km (Aitken, 1997).

The Gog Group presents a seemingly monotonous aspect, and perhaps for this reason it has escaped detailed study. Our work shows that it preserves greater lithologic variety than hitherto has been appreciated. The objectives of this paper are to: (1) revise the existing lithostratigraphy of the Gog Group; (2) provide a general facies description and paleoenvironmental analysis of its constituent units; and (3) discuss the major events in the Early Cambrian evolution of this area of the Western Canada Sedimentary Basin. This work helps write a missing chapter in the Cambrian stratigraphy of North America.

STRATIGRAPHIC BACKGROUND

The Western Canada Sedimentary Basin is a wedge of sedimentary rocks that thickens from its zero-edge on the Canadian Shield westward to the Foreland Belt. The rocks that constitute the fill are Mesoproterozoic to Early Tertiary in age, and reach up to 18 km in thickness in the southern Rocky Mountains and adjacent ranges to the west. They are informally divided into four unconformity-bounded assemblages based on their broad tectonic settings (Monger, 1989). The first assemblage is the Mesoproterozoic Purcell Supergroup (Belt Supergroup in U.S.A.) deposited in an intracratonic basin. The second is the Neoproterozoic Windermere Supergroup, which records rifting and early post-rifting phases of West Laurentia (Ross, 1991). The third assemblage comprises a Lower Cambrian to Triassic succession deposited mainly on a passive continental margin. During the Mesozoic, the tectonic setting shifted completely, such that a mid-Jurassic to Paleocene foreland basin succession constitutes the fourth assemblage. The Gog Group belongs to the third assemblage, with the lower Fort Mountain Formation recording the initial Cambrian phase of development of the passive margin (Fig. 2).

The transition from continental rifting to the establishment of a passive margin is represented in the western Main Ranges of the Rocky Mountains and throughout much of the Omineca Belt by the Windermere Supergroup. Initial Windermere deposition was in half-grabens, followed by a post-rift succession of deep-water siliciclastic strata that locally shoal to platform carbonates (Arnott and Hein, 1986; Ross et al., 1989; Teitz and Mountjoy, 1989; Schwarz and Arnott, 2007). The Miette Group comprises the uppermost part of the Windermere Supergroup and preserves deposits of deep-water turbidite systems, shallow-water carbonate platforms, and stromatolitic reefs. The terminal rifting events are recorded in the Hamill Group of the central Purcell Mountains (Devlin and Bond, 1988) and the Jasper Formation of the southern Rocky Mountains (Fig. 2) (Bond and Kominz, 1984; Lickorish and Simony, 1995). Syn-rift volcanic rocks in the Hamill Group yield zircon ages of 569.6 ± 5.3 Ma (Colpron et al., 2002).

The Gog Group overlies different units of the Miette Group. At Lake Louise, shallow-marine sandstone of the Fort Mountain Formation rests with an erosional contact upon slope-deposited sandstone and shale, and conglomeratic submarine canyon fills belonging to the Hector Formation (Aitken, 1969; Arnott and Hein, 1986). At Bow Peak, an angular unconformity divides these two units (Aitken, 1969). To the southeast, at Castle Mountain, the Fort Mountain Formation abruptly overlies the Corral Creek Formation, a unit stratigraphically lower than the Hector Formation (Fig. 2).

By contrast, at Mount Assiniboine a basal pebble- and cobble-conglomerate of fluvial aspect erosionally overlies deep-marine shale and sandstone of the Miette Group. At Redoubt Mountain and at Mount Chephren, deep-marine conglomerates of the Miette Group are overlain erosionally by sandstone and conglomerate of the Jasper Formation that were deposited in axial fluvial systems reflecting the general orientation of the half-grabens. Conglomerate in the Miette Group contains poorly sorted matrix in which the grain size varies between fine sand and granule, and which contains large micas and up to 10% feldspar. The matrix in the Jasper Formation is well-sorted, fine-grained quartz sandstone with a feldspar content that rarely exceeds 1% (Palonen, 1976).

The Jasper Member of the McNaughton Formation unconformably overlies the Yellowhead carbonate platform, and mudstone and sandstones included in the East Twin and Byng formations of the upper Miette Group (Young, 1979; Teitz and Mountjoy, 1989; Hein and McMechan, 1994). A karst surface is present at the Miette–Gog unconformity at Mount Fitzwilliam (Teitz and Mountjoy, 1989). The unconformity between the Neoproterozoic and Cambrian in the southern Rocky Mountains occurs at the base of the Fort Mountain Formation. It records the start of a renewed transgressive phase in West Laurentia and the initiation of a stable passive margin.

HISTORICAL STRATIGRAPHIC NOMENCLATURE

Stratigraphic subdivisions for Lower Cambrian strata of the Banff area, southern Rocky Mountains have been in use since the late 19th century. McConnell (1887) subdivided Cambrian units at Castle Mountain into the Bow Valley Group, consisting of sandstone and mudstone, and the overlying Castle Mountain Group, consisting of limestone and dolomite. The Castle Mountain Group was later determined to be of Middle Cambrian age, whereas the lower group is Neoproterozoic to Lower Cambrian. Subsequent work on Lower Cambrian units was undertaken by Walcott (1908a,b) who subdivided siliciclastic strata in the Bow Valley and Kicking Horse Pass region into four units: Fort Mountain, Lake Louise, St. Piran and Mount Whyte formations. Deiss (1939, 1940) examined the strata at Mount Assiniboine, and coined the name Gog Formation to encompass them. In the area of Mount Robson, British Columbia, approximately 300 km to the northwest, Mountjoy (1962) raised the Gog to group status and included in it all cliff-forming strata above the slates of the Miette Group and beneath the basal shale and limestone of the Middle Cambrian Snake Indian Formation. Charlesworth et al. (1967) included a lowermost unit, the Jasper Formation, based on the stratigraphy around Jasper. Fritz and Mountjoy (1975) proposed a stratigraphic scheme consisting of the McNaughton, Mural, Mahto and Hota formations. The Jasper Formation was downgraded to a member of the McNaughton Formation, with its upper boundary at the base of the first sandstone lacking feldspar grains (Lickorish and Simony, 1995). Young

(1979) correlated the McNaughton Formation westward across the Rocky Mountain Trench with the equivalent upper Yankee Belle, Yanks Peak and the Midas formations of the Cariboo Group (Fig. 2). Farther to the west, correlative Lower Cambrian strata in the central Purcell Mountains are subdivided into Hamill Group, Mohican Formation, Badshot Formation and Lardeau Group (Hein and McMechan, 1994).

The most recent work on Cambrian stratigraphy around the Bow Valley was by Palonen (1976). At Lake Louise, the Cambrian succession was subdivided into eight informal units based on weathering character; these subdivisions were carried into the Jasper area. Desjardins et al. (2010) informally divided the St. Piran Formation into upper and lower portions, based on a newly detected unconformity.

Use of Walcott's original subdivisions has persisted in the Bow Valley area, with the addition of the locally occurring Jasper Formation at the base and the Peyto Formation at the top(Aitken, 1997) (Figs. 2, 3A,B, 4A–C, 5, 7, 8A–C, 9A,B).

The scarcity of body fossils in the Gog Group hampers precise correlation. However, the presence of trilobites of the *Bonnia–Olenellus* Zone in the Mural, Mahto, and Peyto formations (Fritz and Mountjoy, 1975; Aitken, 1997) indicates an Atdabanian age (Cambrian Stage 3). Downie (1982) documented an assemblage of acritarchs that suggested varying degrees of marine influence.

STRATIGRAPHY AND SEDIMENTARY ENVIRONMENTS

The Gog Group records subtidal to intertidal deposition. In describing the formations and members of the Gog Group we use the sandstone classification of Folk (1980) and bed thicknesses are group in five categories: (1) very thin bedded (<1 cm); (2) thin bedded (1–10 cm); (3) medium bedded (10–30 cm); (4) thick bedded (30–100 cm); and very thick bedded (>100 cm). When interpreting their depositional settings, we usean environmental framework for tide-influence shelves in which the positions of storm and fairweather wave-bases delineate three main zones: (1) the outer shelf, below storm-wave base; (2) the inner shelf, above storm wave-base and below fairweather wave-base; and (3) the shallow subtidal zone above fairweather wave-base. In wave-dominated areas, the third zone is denominated as the shoreface. The intertidal area lies landward of the shallow-subtidal environment (Fig. 6). The basic criterion for the distinction between inner-shelf and shallow-subtidal environments is the presence in the former of laterally continuous thin beds of mudstone intercalated with cross-stratified sandstone sets. These continuous mudstone beds in the inner-shelf environment record suspension fall-out in a bathymetric position below fairweather wave-base and are not genetically related to bedforms, as mud can also be presenst in bottomstes or as drapes (Johnson and Baldwin, 1996).

The Gog Group contain four main types of subtidal deposits, encompassing compound-dune fields, sand sheets, sand ridges and dune patches. Compound-dune fields, formerly called sandwaves (Allen, 1980), are characterised by sigmoidal and planar cross-stratified sandstones grouped in coarsening- and thickening-upward packages (Dalrymple and Choi, 2006). Sand-sheet complexes are also composed of compound dunes but distributed in three adjacent subenvironments: core, front and margin (Stride et al., 1982, Desjardins et al., 2010). The core of the complex is a high-energy area recorded by medium- to thick-bedded, tabular beds of planar and trough cross-stratified and planar compound cross-stratified sandstone. A very coarse-grained sandstone and conglomerate lag capping cross-stratified sandstone records the zone of highest energy. The front is a moderate-energy area adjacent to the core located further down the sediment transport path, if not intensively bioturbated, is characterised by low-angle compound cross-stratified sandstone with local occurrence of interbedded very thin-bedded, ripple cross-laminated sandstone and mudstone. The margin of the complex is a low-energy area adjacent to the front and off the flanks of the complex located even further down the sediment transport path. It comprises intercalated very thin- to thin-bedded, rippled cross-laminated sandstone and mudstone. Sand ridges are large, elongated sandbodies characterised by large-scale compound cross-stratified sandstone associated with lateral accretion surfaces. Coarsening- and thickening-upward intervals are common (Snedden and Dalrymple, 1999). Dune patches develop on sand-starved areas of the shelf, and their deposits are characterised by lenticular compound cross-stratified sandstone encased in mudstone-dominated facies.

JASPER FORMATION

The Jasper Formation crops out in the northern part of the Bow Valley, and northward to Jasper where it is considered a member of the McNaugton Formation. Its type section is at Pyramid Mountain (Charlesworth et al., 1967). The mountainside above the northwestern shore of Cirque Lake, where the formation is approximately 600 m thick, is a suitable reference section for the Bow Valley region (Fig. 10A). It pinches out to the south, being only 0.5 m thick at Redoubt Mountain (Fig. 4A), and is absent around Lake Louise, at Bow Peak and at Castle Mountain (Figs. 1, 4C).

Boundaries

The Jasper Formation unconformably overlies the Miette Group. Its lower boundary at Cirque Lake is placed at the sharp contact between pebbly sandstone and underlying shale (Fig. 10A). The upper boundary is located at the base of the Fort Mountain Formation (Fig. 10B), where subarkosic and pebbly sandstone is overlain by well-sorted, rounded pebbly quartz sandstone lacking feldspar.

Description

The Jasper Formation is almost entirely composed of medium- to very thick-bedded, poorly to well-sorted subarkosic sandstone, pebbly sandstone, and pebble conglomerate. The sandstone bodies are tabular to lenticular, and numerous channel-like features are present (Fig. 10C). Subordinate purple silty sandstone and siltstone intervals are present.

The Jasper Formation was not studied in detail during the present work. Reconnaissance study suggests that it contains five sedimentary facies, which are described briefly here: (1) medium- to thick-bedded, trough cross-stratified, medium- to very coarse-grained sandstone, with rounded to subangular pebbles locally present (S_T) (Fig. 10D, E); (2) medium- to very-thick bedded, planar cross-stratified, fine- to very coarse-grained sandstone, locally containing rounded to subangular pebbles (S_P) (Fig. 10D); (3) thin- to medium-bedded, sharp-based, normally graded, medium- to very coarse-grained sandstone, commonly with subangular to rounded pebbles at the base of individual beds(S_G) (Fig. 10F, G); (4) erosionally based, thin- to medium-bedded, rounded to subangular, cross-stratified, clast-supported pebble conglomerate with a fine- to medium-grained sandstone matrix (Gp, G_T) (Fig. 10D, G); and (5) purple-weathering, thick- to very thick-bedded, laterally continuous, sandy siltstone (Fig. 10C). Locall,y fining-upward intervals capped by planar cross-stratified sandstone (S_P) are present.

Sedimentary environment

Based on reconnaissance work our prelimany interpretations suggest deposition in a fluvial environment. Lickorish and Simony (1995) interpreted these strata represent an axial drainage fluvial system parallel to the walls of pre-existing half-grabens. Coarse-grained facies record deposition on a braid-plain. The trough cross-stratified facies (S_T) is the product of the migration of transverse 3D dunes within channels. The clast-supported pebble conglomeratic facies (G_T) is interpreted as channel-lag deposits. Graded beds (S_G) suggest waning flows, whereas trough cross-stratified sandstone (S_T) suggests the occurrence of episodic flood-like discharges. Where these facies are interlayered, they record alternating flow conditions. Fining-upward intervals capped by planar cross-stratified sandstone (S_P) record lateral migration of channel bars.

FORT MOUNTAIN FORMATION

The Fort Mountain Formation is a well-sorted sandstone unit with common pink to red hematite staining, and is uniformly and continuously distributed over the Bow Valley area (Fig. 11A). In some sections leisegang bands have the appearance of overturned cross-bedding (Fig. 11G). The formation is 70 m thick on average and pinches out to the east and southeast, reaching a minimum thickness of 40 m at Castle Mountain (Fig. 4C). Walcott (1908b) established the type section at Ptarmigan Peak (Fig. 4B) but included within the formation the conglomeratic unit of the Hector Formation (Arnott and Hein, 1986). Additional sections are at Lake Louise, Lake O'Hara (Figs. 8A, 11B), on the southeastern slope of Ptarmigan Peak (Fig. 4B), and at Saddle Mountain (Fig. 1).

Boundaries

This unit erosionally overlies the Jasper Formation in the northern portion of the Bow Valley (Fig. 10B) and at Redoubt Mountain (Fig. 1, 4A). Around Lake Louise and at Bow Peak, it overlies the Hector Formation, and at Castle Mountain it rests on the Corral Creek Formation (Aitken, 1969). The lower contact is sharp. Locally, the lowest 20 cm of the formation consists of well-rounded, medium- to very coarse-grained sandstone containing scattered, rounded pebbles that are 0.5–2.0 cm in diameter (Fig 11C). On the western slope of Redoubt Mountain, the basal deposits are fine-grained sandstone. However, 1–1.5 m above the base, some beds contain sub-rounded to rounded pebbles in a very coarse- to medium-grained sandstone matrix. The contact with the overlying Lake Louise Formation is gradational, and is placed at the base of the first thin shale bedded.

Description

The Fort Mountain Formation is characterized by very well-sorted, medium- to fine-grained sandstone. Beds commonly are tabular to lenticular, with sharp, slightly erosional bases, planar to wavy tops, and scattered reactivation surfaces. Individual beds are generally 7–20 cm thick and stacked, forming tabular sets 50–100 cm thick. Mudstone laminae and intraclasts are rare, The unit forms a coarsening-upward succession.

Twelve facies are defined for this unit (Table 1), and grouped into three facies associations. FA-1 comprises thin beds of ripple and planar cross-laminated sandstone

(S_{R1}, S_{L1}) grouped in medium to thick bedsets intercalated with thin to medium siltstone laminae (Slt), in which stylolites are locally developed. FA-2 comprises thin- to thick-bedded planar (S_{P1}), trough (S_{T1}), herringbone (S_{HGB}) and hummocky (S_{HCS1}) cross-stratified sandstone, and planar laminated sandstone (S_{L1}) intercalated with very thin-bedded siltstone (Slt). Locally, convolute (S_{CON}), structureless (S_{M1}) or ripple cross-laminated (S_{R1}) sandstone is interbedded (Fig. 11D–G). FA-3 is composed of medium-bedded lenticular sandstone beds (S_{SIG1}) intercalated with very thin- to thin-bedded mudstone (Mdst), medium-bedded bioturbated sandstone (S_{B1}), and thick-bedded sigmoidal cross-stratified sandstone (S_{SIG1}). *Skolithos* pipe rock (S_{B1}) ichnofabrics are common only at the top of this unit.

Sedimentary environment

The Fort Mountain Formation records the presence of a transgressive sea over an area of low relief. A basal lag of scattered pebbles in a coarse-grained sandstone matrix was formed by waves and tidal currents during the initial transgression. Later, sand was deposited in a shallow-subtidal environment above fairweather wave-base (FA-1 and FA-2). FA-1 is interpreted as having formed in areas of moderate to low current and wave energy, possibly in protected areas behind and between shoals. FA-2 represents shallow-subtidal deposition under conditions of stronger current and wave energy. Along with weather-driven currents (i.e. longshore, wind drift and storms), strong tides swept the shallow subtidal environment as indicated by bidirectional, medium- to thick-bedded cross-stratified sandstone. Low-energy periods allowed the deposition of thin-bedded siltstone. FA-3 records migration of compound dunes on the inner shelf. Mudstone layers at the foresets of sigmoidal cross-stratified sandstones were deposited as suspension fall-out during low-energy periods (Allen, 1980).

LAKE LOUISE FORMATION

The Lake Louise Formation is a recessive-weathering, locally highly bioturbated, heterolithic unit with a characteristic dull green weathering colour (Fig. 12A, B). It thickens towards Lake Louise with a maximum thickness of 25 m, and pinches out to the east and south. On the slopes of Storm Mountain, at Vermillon Pass, the Lake Louise Formation is substantially sandier than at Bow Peak (Figs. 11A, 12A). Walcott (1908b) designated the 35 m thick section on the northern slope of Fairview Mountain on Lake Louise as the type section (Figs. 8B, 12B).

Boundaries

This unit gradationally overlies the Fort Mountain Formation (Fig. 11B). Its lower contact is placed at the base of the first shale above which the bedsets are heterolithic. The contact marks a change from the upward-coarsening Fort Mountain Formation to an upward-fining succession. The upper boundary is gradational, and is placed at the first occurrence of a very thick-bedded sandstone unit, which may contain thin mudstone laminae (Fig 12A–B), corresponding to the base of the St. Piran Formation.

Description

The Lake Louise Formation consists of intercalated very well-sorted, fine- to very fine-grained sandstone and shale, with abundant lenticular and wavy sandstone beds.

Intraclasts are common in medium- to coarse-grained sandstone facies. Gutter casts and variably shaped and crumpled shrinkage cracks (‘syneresis’ cracks, sandstone dikelets) are present locally. The formation fines upward in its lower part but coarsens upward in its upper part.

Eight facies are recognized in this unit (Table 2) and grouped into three associations (Fig. 12C). FA-4 comprises medium- to very thick-bedded shale (M_S) intercalated with thin- to medium-bedded wavy- and lenticular-bedded, very fine-grained sandstone (H_1). Bioturbation is scattered and characterised by horizontal and sub-horizontal trace fossils, such as *Planolites* isp., *Teichichnus rectus*, *Cruziana* isp., *Rusophycus jenningsi,* and *Rusophycus pectinatus* (Fig. 12C). FA-5 is composed of intercalated thin-bedded flaser- (S_{F1}), wavy- and lenticular-bedded, very fine-grained sandstone (H_1), and thin-bedded, rippled cross-laminated (S_{R2}) and planar-laminated (S_{L2}) very fine-grained sandstone (Fig. 12D–I). Thin-bedded hummocky cross-stratified (S_{HCS2}) and intensely bioturbated (BI 5–6) sandstone facies (S_{B3}) are also present in this association. Abundant horizontal and subhorizontal arthropod and worm trace fossils, including *Cheiichnus* isp., *Conostichus* isp., *Cruziana* isp., *Diplichnites* isp., *Halopoa* isp., *Helminthopsis* isp., *Dimorphichnus* isp., *Palaeophycus* isp., *Phycodes* isp., *Planolites* isp., *Rhizocorallium* isp., *Rusophycus jenningsi*, *Rusophycus pectinatus*, *Teichichnus rectus* and *Trichophycus* isp. Vertical forms include *Diplocraterion parallelum*, *Rosselia* isp. and *Skolithos linearis*. FA-6 includes lenticular, medium- to thick-bedded, planar-cross stratified, fine- to medium-grained sandstone (S_{P2}), commonly containing mudstone within bedsets (Fig. 12J), and medium-bedded, bioturbated fine-grained sandstone (S_{B2}) dominated by *Skolithos linearis.*

Sedimentary environment

The Lake Louise Formation records outer- to inner-shelf sedimentation characterised by low rates of sand transport to the shelf. The base of this unit marks a change from a shallow-subtidal to inner-shelf environment; the fine-grained facies record dominantly low-energy conditions, in contrast to the underlying Fort Mountain Formation. FA-5 represents a low-energy area of the inner shelf, characterised by mud and sand patches, interrupted by storm episodes and dune migration. The common presence of hummocky cross-stratified sandstone suggests conditions above storm wave-base (Johnson and Baldwin, 1996). By contrast, FA-4 lacks hummocky cross-stratified sandstone, and its lithology of shale intercalated with very thin-bedded sandstone suggests sedimentation below or close to storm wave-base in an outer- to inner-shelf environment where suspension-fallout was the dominant process, punctuated with minor sand sedimentation events probably induced by storms. FA-6 records dune patches which develop under conditions of relatively low sediment supply on the inner shelf. This is suggested by the lenticular geometries of the planar cross-stratified beds preserving bedforms on tops and the relatively high mud content within bedsets.

ST. PIRAN FORMATION

The type section of the St. Piran Formation was defined by Walcott (1908a) on the southeastern slope of Mount St. Piran in the vicinity of Lake Louise, with its base at Lake Agnes. It was originally described as ‘mainly grey, quartzitic sandstone, with a few bands of siliceous shale’ (Walcot, 1908a, p. 5). Aitken (1997) suggested the abandonment of the name St. Piran Formation after he redefined the Peyto Member as a formation, as the former could not be recognized everywhere in the southern Rocky Mountains. However, we consider that a better solution is the redefinition of the St. Piran Formation (Fig. 3A), because if abandoned, some 800 m of the Gog Group would remain undivided. We have recognised this formation in all the studied localities, in contrast to Atiken's (1997) observations, and propose four members for the area around Lake Louise, Lake O'Hara and Redoubt Mountain: (1) Lake O'Hara; (2) Lake Oesa; (3) Moraine Lake; and (4) Wiwaxy Peaks members (Figs. 3A,B, 4A, B, 5, 8C, 9B). Each of these members represents a shoreline progradation. They cannot be differentiated, however, on Castle Mountain area where the St. Piran Formation pinches out and the whole Gog appears is thinner (Fig. 4C). We have not studied the formation north of Bow Pass in order to determine the lateral persistence of the individual members.

A principal reference section is proposed on the southern slope of Mount Huber, with its base below Lake Oesa, where the St. Piran Formation is 700 m thick (Fig. 3B). The Lake O'Hara, Lake Oesa and Moraine Lake members are described in detail here, while the Wiwaxy Peaks Member is described briefly, as these strata have been discussed elsewhere (Cant and Hein, 1986; Hein, 1987; Hein et al., 1991).

Lake O'Hara Member

The Lake O'Hara Member is a resistant, overall thickening- and coarsening-upwards unit (Fig 8C, 13A). It exhibits a wide range of weathering colours; its lower part is dark-green to grey, while its upper part varies between light-grey, pink and orange. It reaches its maximum thickness (195 m) at Lake O'Hara and pinches out to the east; it is of uniform thickness parallel to the Bow Valley. A composite type section is designated comprising two overlapping sections, one on the western flank of Yukness Mountain and a second on a cliff at the southwestern side of the Opabin Plateau by Mary Lake (Fig. 8C).

Boundaries

The Lake O'Hara Member gradationally overlies the Lake Louise Formation at all localities. The lower contact is placed at the base of the first very thick-bedded sandstone, which contains thin mudstone laminae (Figs. 8B, 13B). The upper boundary is placed at the base of red, thin- to medium-bedded, medium- to coarse-grained sandstone, belonging to the Lake Oesa Member, which erosionally overlies thick- to very thick-bedded, medium- to coarse-grained sandstone; this is a useful surface for correlation (Fig. 7). The lower boundary is best exposed on the northern flank of Fairview Mountain at Lake Louise (Figs. 13A, B), whereas the upper boundary is best observed near Lake Oesa.

Description

Overall, the Lake O'Hara Member coarsens and thickens upward. It can be subdivided into three intergrading intervals (Figs. 13A, 14A, B). The lowest interval is characterised by thin- to medium-bedded, well-sorted, fine- to medium-grained sandstone intercalated with thin- to very thin-bedded, lenticular- and wavy-bedded sandstone and structureless-appearing mudstone. The middle interval is distinguished by the dominance of thick- to very thick-bedded *Skolithos* pipe rock intercalated with minor thin- to very-thin bedded, lenticular- to wavy-bedded sandstone. Shrinkage cracks and gutter casts are sporadically present. The uppermost interval is characterised by amalgamated, medium- to thick-bedded tabular sandstone beds with scattered and rare mudstone laminae.

Ten facies are recognised in the Lake O'Hara Member (Table 3), and grouped into seven associations, FA-5 and FA-6 being also present in the Lake Louise Formation. The lowest interval comprises FA-5 and FA-6 (Fig. 13C–F). FA-5 is composed of intercalated thin-bedded, wavy- and lenticular-bedded, very fine-grained sandstone (H_2), thin-bedded, ripple cross-laminated (S_{R3}) and planar-laminated (S_{L3}), very fine-grained sandstone, and thin- to medium-bedded massive mudstone (M_2) (Fig. 15B–D). Shrinkage cracks are present sparsely in mudstone. Scattered horizontal and sub-horizontal burrows (e.g. *Planolites* isp., *Teichichnus rectus, Rusophycus* isp. and *Cruziana* isp.) occur in the wavy- and lenticular-bedded facies (H_2). FA-6 consists of medium-bedded, low-angle and planar cross-stratified, fine- to medium-grained sandstone (S_{P3}) forming superimposed sets separated by inclined, slightly erosive surfaces (Fig. 13D–F). These surfaces are concave upwards or sigmoidal, and merge into FA-5 (Fig. 15A). Cross-stratified sets are 50–200 cm thick. Rare, vertical burrows belonging to *Skolithos linearis* occur within cross-stratified beds.

The pipe rock-dominated interval includes FA-7, FA-8 and FA-9. FA-7 is characterised by 5–10 cm thick, flaser- (S_{F2}), wavy- and lenticular-bedded sandstone (H_2), medium- to thick-bedded, very fine- to fine-grained hummocky cross-stratified sandstone (S_{HCS3}), and thin-bedded, planar laminated, very fine- to fine-grained sandstone (S_{L3}) (Fig. 15D–E). Vertical burrows belonging to *Rosselia* isp. occur scattered in hummocky cross-stratified sandstone (S_{HCS3}). Horizontal and sub-horizontal *Planolites montanus* and *Teichichnus rectus* are present locally in the heterolithic intervals (Fig

15D). FA-8 comprises thin-bedded intervals of intercalated flaser- (S_{F2}), wavy- and lenticular-bedded (H_2), ripple cross-laminated (S_{R3}), and thin- to medium-bedded trough (S_{T2}) and planar cross-stratified (S_{P3}) sandstone, in 80–300 cm-thick packages. Hummocky cross-stratified sandstone (S_{HCS3}) is also present. Dense populations of *Skolithos linearis* and *Diplocraterion parallelum* are common in the sand-dominated facies giving rise to pipe rock ichnofabrics (Pr) (Fig. 15E–F). Locally, horizontal and sub-horizontal *Planolites montanus*, *Teichnichnus rectus*, and *Rusophycus* isp. are present in wavy- and lenticular-bedded sandstone (H_2). Rarely present are sand-filled molds of fragments of hyolithids and olenellid trilobites of the *Bonnia–Olenellus* Zone .

The upper interval comprises FA-9 which consists of amalgamated cross-stratified sets composed of thick-bedded, structureless-appearing (S_{M2}), planar (S_{P4}) and trough (S_{T3}) cross-stratified fine- to coarse-grained sandstone and medium- to thick-bedded hummocky cross-stratified, fine-grained sandstone (S_{HCS3}) (Fig. 15G). Locally, thin-bedded intervals of wavy- and lenticular-bedded sandstone (H_2) occur intercalated between very thick-bedded sandstone sets. While the lower part of this interval is mainly non-bioturbated, the uppermost part contains abundant large *S. linearis* and *Rosselia* isp. (Fig. 15H) (Desjardins et al., 2010).

Sedimentary environment

The gradational contact between the Lake Louise Formation and the Lake O'Hara Member records the early progradational phase of an inner-shelf compound dune field. The base of the Lake O'Hara Member the presence od larger bedforms is interpreted as an evidence of increased sediment supply due to the migration of larger bedforms (Belderson et al., 1982). FA−5 represents in part an environment similar to that of the Lake Louise Formation, an area of low energy in the inner-shelf, characterised by mud with dune patches offshore of shallower-water compound-dune fields. The frequency with which FA−5 is intercalated with cross-stratified sandstone intervals is greater than in the Lake Louise Formation. Also, structureless mudstone is interpreted to have been deposited as fluid mud, as it lacks lamination and trace fossils (MacEachern et al., 2005).

FA−6 records migration of inner-shelf 3D and 2D compound dunes (Dalrymple and Choi, 2007). These deposits contain few *Skolithos linearis*, suggesting brief colonization windows. Sparse bioturbation and the common presence of structureless mudstone suggest high flocculation rates (e.g. Buatois et al. 2008). Overall, the lower member records progradation of compound-dune fields into a low-energy environment.

The middle part and most of the upper part of the Lake O'Hara Member comprise genetically related facies associations recording a sand-sheet complex in inner-shelf to shallow-subtidal environments (Desjardins et al., 2010). FA−7 is interpreted to have been formed around the margins of a sand-sheet complex, characterised by mud and rippled sand patches. A position above storm wave-base is inferred based on the presence of hummocky cross-stratified sandstone. FA−8 records a more proximal position in the sand-sheet complex than FA-7. The front of the sand-sheet complexes was a moderate-energy environment characterised by medium and small dunes, rippled sand, and mud patches. Common *Skolithos* pipe rock ichnofabrics suggest favourable ecological conditions for suspension feeders and prolonged colonization windows (Desjardins et al., 2010). FA−9 records the migration of medium to large 2D and 3D compound dunes under strong unidirectional currents within the sand-sheet core. The paucity of mudstone in this facies association reflects high-energy conditions typical of shallow-subtidal settings. The presence of pipe rock at the top reflects decreased energy which enabled colonization by suspension feeders.

Lake Oesa Member

The Lake Oesa Member is a recessive, red- to purple-weathering mudstone dominated unit. It characterized by fining-upwards succession with common sandstone packages at their bases. (Fig. 9A). It is continuously distributed in the region and is a distinctive stratigraphic marker (Figs. 3B, 1A,B, 11A, 13A, 16A). It reaches its maximum thickness of slightly more than 9 m in the Lake O’Hara area, from whence it pinches out to the east. Its type section is below Lake Oesa, near Lake O’Hara.

Boundaries

The lower boundary is well exposed below Lake Oesa and at Lake Louise (Figs. 16B, C, D) and is placed where red, thin- to medium-bedded, medium- to coarse-grained sandstone erosively overlies grey, thick- to very thick-bedded, medium- to coarse-grained sandstone of the Lake O’Hara Formation. The upper boundary is the base of green to light brown sandstone and siltstone of the Moraine Lake Member (Fig. 16D, 17F).

Description

The Lake Oesa Member comprises two facies, grouped in FA-10 (Table 4) and characterised by fining-upward intervals (Fig. 9A). The lower part of each of these cycles is composed of planar and trough cross-stratified fine- to coarse-grained sandstone (S_X), locally containing mudstone laminae, and *Skolithos linearis*. These gradationally pass upward into heterolithic packages of very thin- to thin-bedded intercalated mudstone and wavy-, lenticular- and flaser-bedded sandstone (H_3) (Fig. 17D), commonly exhibiting wrinkle marks, interference ripples (Fig. 17E), scattered regularly polygonal mud cracks (Fig. 17B–C), and an impoverished trace-fossil suite dominated by shallow-tier trace fossils (*Diplichnites* isp., *Helminthopsis* isp., *Helminthoidichnites* isp., *Dimorphichnus* isp. and *Rusophycus carbonarius*).

Sedimentary environment

The erosional contact at the base of the Lake Oesa Member records an abrupt seaward shift of sedimentary environments, characteristic of forced regressions (Plint and Nummedal, 2000). FA-10 represents a tidal-flat complex, comprising two fining-upward progradational cycles which include facies typical of sand-flat to mixed- and mud-flat transitions (Klein, 1977). Polygonal mud cracks record subaerial exposure and desiccation of the sediment.

Moraine Lake Member

The Moraine Lake Member is a coarsening- and thickening-upward sandy unit which is some 250 m thick at Lake O'Hara (Figs. 3A, B, 9B). It represents an overall progradational cycle. Its type section is at the Tower of Babel by Moraine Lake (Fig. 16A). Accessible outcrops of its uppermost part are in roadcuts along Highway #1 by

Sink Lake. Hein et al. (1991) provided a sedimentologic summary of these strata, but misidentified them as belonging to the Fort Mountain Formation.

Boundaries

The base of the Moraine Lake Member is a sharp contact with the Lake Oesa Member (Fig. 16B) where hummocky cross-stratified sandstone overlya red mudstones of the lower unit.. The upper boundary is gradational with intercalated thin- to very-thin bedded sandstone and mudstone of the Wiwaxy Peaks Member succeeds very thick-bedded sandstone of the Moraine Lake Member (Figs. 3A, 9B, 16E, F). The lower boundary is best exposed on the southern flank of Mount Huber below Lake Oesa (Fig. 16B, D).

Description

The Moraine Lake Member is composed of seven facies that we group into five facies associations (Table 4). It can be subdivided informally into three intervals. The basal interval is overall recessive, green to grey in colour, and includes FAs–11 to 14, with FA-12 being the most common. The lowermost part of the basal interval consists of FA-11, which is composed of hummocky cross-stratified sandstone (S_{HCS4}) and planar laminated very fine-grained sandstone and siltstone (S_{L4}) (Fig. 17F). It locally contains *Cruziana* isp., *Rusophycus* isp. and rare but dense assemblages of *Bergaueria* isp. (Magwood and Pemberton, 1990). This is sharply overlain by deposits of FA-12 which make up most of the middle part of this interval (Figs. 16D, 17F). FA-12 is heterolithic, consisting of thin- to very thin-bedded mudstone and sandstone (H_4), locally inclined on top of concave surfaces (Fig. 17G). FA-13 is composed of lenticular, thick- to very thick-bedded, cross-stratified sandstone that contains bundles, reactivation surfaces, abundant mudstone laminae and curved to sigmoidal foresets which grade to horizontal rippled bottomsets (S_{SIG2}) (Figs. 17H, 18A)FA-. The upper part of the basal interval (FA-14) is sharp based (Fig. 18A–B) and is composed of amalgamated, fine- to medium-grained, cross-stratified sandstone with undulating bed tops (S_{T4}) (Fig. 18B).

The medial interval os composed of FA-15. It consists of thick- to very thick-bedded coarsening- and thickening-upward cycles that define an overall thickening-upward succession. The lower part of each cycle is lenticular-bedded sandstone and structureless-appearing mudstone with rare *Planolites* isp., intercalated with ripple cross- and planar-laminated sandstone (H_5) and thin- to medium-bedded cross-stratified sandstone (S_{P3}) (Fig. 18C). The upper part of each cycle is thick to very thick, relatively tabular bedsets of planar and trough cross-stratified sandstone (S_{P3}, S_{T5}) (Fig. 18D). Bioturbation within the medial interval is limited to scattered, thin to medium beds of *Skolithos* pipe rock.

The upper interval is characterised by FA-16, which is composed of resistant, amalgamated tabular beds of planar cross-stratified, fine- to medium-grained sandstone (S_{P4}), commonly intercalated with thin-bedded ripple cross- and planar-laminated sandstone (S_{R4}, S_{L5}) (Fig. 18E). Locally, wave-ripples draped by a thin lamina of siltstone are present at the top of the tabular cross-stratified beds.

Sedimentary environment

FA-12 sharply overlies FA-11, and is interpreted to record the progradation of a shoreface after a transgressive event. FA-12 records deposition in a tide-dominated setting in which isolated subaqueous dunes migrated. FA-13 represents shallow-subtidal compound dunes. The stacking pattern of this succession is progradational, and its deposits contain a depauperate trace-fossil suite presumably related to stress factors, such as salinity fluctuations and high flocculation rates, typical of deltaic settings (MacEachern et al., 2005; Buatois et al., 2008; Carmona et al., 2009).

FA-14 records a second transgressive shoreface, abruptly overlying prodelta-like deposits (FA-12), which passes to inner-shelf to shallow-subtidal compound dune fields represented by FA-15. Similar to FA-12 and FA-13, these deposits also contain a depauperate trace-fossil suite. FA-16 is similar to FA-1 and FA-2, and is likewise interpreted to have been deposited in shallow-subtidal compound-dune fields.

Wiwaxy Peaks Member

The Wiwaxy Peaks Member is a sandstone-dominated unit with an overall coarsening- and thickening-upward stacking pattern (Figs. 3A, B, 4A, B, 9B). It records the last progradational phase in the Bow Valley area before its transition to a carbonate ramp. Its type section is on the southern flank of the Wiwaxy Peaks by Lake O'Hara (Figs. 3B). A reference section is on the slopes of Mount Temple in the Larch Valley–Sentinel Pass area (Fig. 16F). In contrast to the other members, outcrops of this member are of difficult access due to steep cliff faces. However, the middle part of it is well exposed in roadcuts along Highway #1 by the Spiral Tunnels.

Boundaries

The Wiwaxy Peaks Member lies gradationally upon the Moraine Lake Member (Figs. 3A, 16F). Its basal contact is the base of the first shale above which bedsets are heterolithic. The upper boundary is gradational or in places erosional, and corresponds to the base of the Peyto Formation (Figs. 16F, 17) (Palonen, 1976; Aitken, 1997).

Description

The Spiral Tunnels section consists of compound cross-stratified sandstone, in which reactivation surfaces are common, organized into 2–6 m thick coarsening-upward packages (Fig 19A–C). In contrast to sand-sheet and shallow-subtidal deposits elsewhere in the Gog Group, which are relatively tabular, those in the Wiwaxy Peaks Member tend to be lenticular and markedly asymmetric, developing foresets greater than 3 m thick (Fig. 19A). Bottomsets comprise mudstone and lenticular-bedded sandstone intercalated with thin- to medium-bedded ripple cross-laminated and herringbone, planar and trough cross-stratified sandstone (Fig. 19B).In the bottomsets trace fossils are mainly horizontal and sub-horizontal: *Cruziana* isp., *Dimorphichnus* isp., *Planolites montanus*, *Palaeophycus annulatus*, *Phycodes* isp. and *Rusophycus* isp. *Skolithos linearis* is the only vertical form. Topsets are characterised by erosively based and thick-bedded cross-stratified sandstone (Fig. 19B–C). Above an interval of topset deposits are two thickening-upwards intervals consisting of thin- to thick-bedded, hummocky and trough cross-stratified, and planar laminated, well-sorted, fine- to medium-grained sandstone (Fig. 19D).

By contrast, in the Larch Valley–Sentinel Pass area, where the middle part of the member is well exposed, very thick-bedded compound cross-stratified sandstone, similar to that seen along Highway #1 by the Spiral Tunnels, passes vertically into amalgamated, lenticular, thick to very thick-bedded, sigmoidal compound cross-stratified sandstone.

These sandstone beds are internally characterised by bundles, reactivation surfaces, mudstone laminae, and asymptotic foresets which grade to horizontal rippled bottomsets (Fig. 19E). Trace fossils in the Larch Valley–Sentinel Pass area include horizontal and sub-horizontal forms belonging to *Cruziana* isp., *Palaeophycus tubularis*, *Rusophycus* isp., and *Trichophycus* isp. Vertical forms belonging to *Arenicolites* isp., *Bergaueria* isp., *Rosselia socialis, Rosselia* isp. and *Skolithos linearis* are locally present.

Interpretation

Outcrops along Highway #1 by the Spiral Tunnels were interpreted to have been deposited as part of an inner-shelf sand ridge by Hein (1987). The upper part of this section is interpreted as two parasequences comprising lower- to upper-shoreface deposits. Above these, the section is repeated by faulting. The sigmoidal compound cross-stratified beds in the Larch Valley–Sentinel Pass area record periodic migration and deposition of straight- to slightly sinuous-crested compound dunes. Reactivation surfaces are carved by the migration of superimposed dunes on the lee side. Rippled bottomsets suggest a decrease of current strength at the toes of these bedforms. Mudstone laminae are from mud drapes due to periods of dune inactivity (Nio and Yang, 1991).

PEYTO FORMATION

Peyto Formation is a resistant, locally dolomitized limestone with minor intercalations of sandstone and shale, that was deposited on a carbonate ramp (Aitken, 1997). Fossils of the Peyto Formation belong to the Atdabanian (Cambrian Stage 3) *Bonnia–Olenellus* Zone (Palonen, 1976; Aitken, 1997). Its type section is at Mount Weed, southeast of

Mount Chephren. It is dominated by coarse-grained ooid, bioclast and oncoid grainstone and packstone, with interbedded lime mudstone. Sandy limestone commonly intergrades with calcareous sandstone.

Its lower contact is conformable and locally erosional, and its upper boundary is disconformable with the Mount Whyte Formation (Fig. 20). It thins to the westand east of Lake Louise It is absent south of Lake Louise andat Mount Odaray, Mount Stephen, Mount Field and south of Vermilion Pass. However it reappears 2 km northeast of Field. This suggests that the Peyto Formation was eroded at the crest of a subtle anticlinal feature along the axis of the Kicking Horse Rim (Aitken, 1971; Palonen, 1976; Aitken, 1997). Alternatively, the Peyto Formation might not have been deposited south of Lake Louise, if this sector was a high (Aitken, 1997).

THE GOG GROUP IN MOUNT ASSINIBOINE AREA

Deiss (1940) established the type section of the Gog Group on the slopes of The Towers by Wonder Pass. We propose a principal reference section on the eastern side of Sunburst Peak , which has an easier access (Fig. 21A). The Gog Group at Mount Assiniboine is much thinner than in the Bow Valley area, reaching only some 380 m, and most of it can be correlated to the Fort Mountain Formation, Lake Louise Formation, and Lake O’Hara Member of the St. Piran Formation (Fig. 7) (Desjardins et al., 2010). It unconformably overlies the Miette Group (Fig. 21B). Facies above and below this contact differ from site to site, suggesting truncation of different levels of Miette strata. The basal thick- to very thick-bedded clast-supported pebble conglomerate is composed of very well-rounded quartzite, suggesting the influence of a positive-relief area near Mount Assiniboine during deposition. The upper boundary is also unconformable and represents an important unconformity with the overlying Middle Cambrian Naiset Formation.

Although not studied in detail here, the Gog Group at Sunburst Peak can be subdivided into five distinctive units. The lowermost unit comprises clast-supported cobble conglomerate and matrix-supported conglomerate with a medium- to coarse-grained sandstone matrix, interbedded with medium- to coarse-grained sandstone. Angular, tabular-shaped mudstone pebbles derived from the Miette Group occur scattered in the lowermost part. Above by a transgressive surface (Fig. 21C), the second unit reaches some 160 m in thickness, and is composed of 2–10 m thick, coarsening- and thickening-upward cycles. Each cycle starts with thin- to medium-bedded, cross-stratified and ripple cross-laminated, fine- to medium-grained sandstone. These are overlain by erosionally based, medium- to thick-bedded, planar and trough cross-stratified, medium- to coarse-grained sandstone. Bioturbation occurs only locally, and is characterised by clusters of *Skolithos linearis*.

The third unit is 75 m thick, and consists of coarsening- and thickening-upward cycles comprising interbedded shale and wavy-bedded, fine- to medium-grained sandstone, containing abundant *Rusophycus pectinatus*, *Rusophycus jenningsi*, and *Cruziana* isp. in their lower portions. These are overlain by medium- to thick-bedded planar and trough cross-stratified sandstone. This unit is capped by 20 m of intercalated fine- to very fine-grained sandstone and shale, with abundant lenticular- and wavy-bedded sandstone and mudstone (Fig. 21D). *Rusophycus* isp. and *Cruziana* isp. are abundant in these facies. Lithoestratigraphically, this interval is correlative to the Lake Louise Formation. A maximum flooding surface is inferred to be present within this interval. The upper part is composed of coarsening- and thickening-upward cycles, with the same arrangement of facies than those of its lowermost portion.

The fourth unit coarsens and thickens upward. Its lowermost part is composed of thick- to very thick-bedded *Skolithos* pipe rock interbedded with lenticular to wavy-bedded, hummocky and planar cross-stratified sandstone. These facies are gradationally overlain by bedsets of medium- to thick-bedded, planar and trough cross-stratified sandstone. Locally, very thin-bedded mudstone is interbedded within sandstone which commonly contains intraclasts of mudstone. Desjardins et al. (2010) interpreted this interval at Mount Assiniboine as the progradation of a sand-sheet complex.

The fifth unit in not always present due to erosion related to the sub-Middle Cambrian unconformity. It gradationally and locally erosionally overlies thick-bedded sandstone, and comprises red, amalgamated thin- to medium-bedded, moderately sorted, fine- to very coarse-grained sandstone, reaching some 30 m in thickness (Fig. 21E). Red to purple mudstone and lenticular bedded sandstone are similar to those of the Lake Oesa Member. Above a flooding surface, a green to gray, heterolithic package composed of intercalated mudstone and very thin- to thin-bedded sandstone constitutes the top of the Gog Group.

BASIN EVOLUTION

The Gog Group represents the early development of a passive margin under enhanced siliciclastic sediment supply. Accommodation was sustained by the high rates of thermal subsidence and sea-level rise which are also evident in other correlative sections of Laurentia and around the world. The Gog Group records numerous pulses of progradation before the initiation of carbonate sedimentation and major transgression far into the cratonic interior. Five different stages in the evolution of this part of the Western Canadian Sedimentary Basin are envisaged for Gog Group time.

LATE RIFTING

The Jasper Formation records a late rifting event. Extensional faults created local accommodation space above the hanging walls adjacent to the footwalls (Fig. 22). The stratigraphy of the rocks immediately above and below the base of the Gog Group points to the existence of a higher block in the area of Castle Mountain, and northwest of there, at Redoubt Mountain, the Jasper Formation is only 0.5 m thick. The basal conglomerate at Mount Assiniboine could be related to a positive area uplifted during this time, and as a consequence might be correlative to the Jasper Formation. However, its matrix lacks feldspar, as does the sandstone interbedded with it, in contrast to the sub-arkosic Jasper Formation. This could suggest also the influence of multiple source areas. The Mount Assiniboine area was likely a northern extension of Montania. During the Cambrian, Montania was an exposed landmass of Belt-Purcell rocks (Norris and Price, 1966; Slind et al., 1994), which could have been the source for the basal conglomerate pebbles and cobbles in Mount Assiniboine. At Jasper, the lower member of the localized McNaughton Formation has also been related to rifting events (Lickorish and Simony, 1995).

INITIATION OF TRANSGRESSION

The initiation of Early Cambrian transgression on the stabilized passive margin is recorded at the base of the Fort Mountain Formation, where a transgressive lag is locally present. In the Bow Valley area, where shallow-subtidal sandstones are dominant, the

Fort Mountain Formation can be traced without major thickness changes along the western margin of the valley, reflecting creation of accommodation during transgression.

Most of the sedimentary structures in this formation are related to tidal currents. In the Mount Assiniboine area, the Fort Mountain Formation is not recognized and the lower interval of the Gog Group comprises coarsening- and thickening-upwards intervals that are only locally bioturbated. This suggests a shallower, higher energy setting, possibly closer to river deltas that may have delivered sediment which was then transported north, parallel to the shoreline east of the Bow Valley. North of the study area, paleocurrents in the McNaughton Formation suggest a different source area, related to the Peace-Athabasca arch (Young, 1979).

PEAK OF TRANSGRESSION

A regional maximum flooding event is recorded within the fine-grained heterolithic deposits of the Lake Louise Formation. Although having variable characteristics, this unit is recognized from Mount Assiniboine to Mount Chephren. North of Mount Chephren, the Sophist Member of the McNaughton Formation is also a recessive interval and correlative to the Lake Louise Formation (Lickorish and Simony, 1995).

During maximum transgression, environments were characteristically of lower energy, and suspension fallout and episodic sand sedimentation were the dominant processes. Towards the top of the Lake Louise Formation, the stacking pattern becomes progradational and thin- to medium-bedded cross-stratified sandstone is common.

PROGRADATIONS

Following development of a maximum flooding surface in the Lake Louise Formation, three major progradations are recorded in the St. Piran Formation at Lake Louise and Lake O'Hara. At Redoubt Mountain, the Gog Group is also characterised by three progradations but this interval is not as thick as it is to the west. Not all three progradations are recognised elsewhere. At Mount Assiniboine, only the first progradation is recorded, and preserves features similar to the Lake O'Hara Member, in particular thick- to very thick-bedded *Skolithos* pipe rock. At Castle Mountain, two progradations are recognised, although the first is erosionally cut into the Lake Louise Formation, and both are thinner than the ones to the west, suggesting a position closer to the shoreline. At Jasper, the progradational phase is recorded by the Mahto Formation (Fritz and Mountjoy, 1975).

SEDIMENT DEPLETION AND INITIATION OF CARBONATE SEDIMENTATION

The transition from siliciclastic-dominated to carbonate-dominated sedimentation is recorded by the Peyto Fornation is one of the most important shifts in sedimentation styles in the Western Canadian Sedimentary Basin. The depletion of siliciclastic sediments is related to the eastward migration of the shoreline as the transgression progressed towards the cratonic interior. Shallow-subtidal sands continued to be deposited during the Middle Cambrian as the Basal Sandstone and Finnegan Formation in the subsurface of Alberta and Saskatchewan, and the Flathead Formation in Montana. Most of the Peyto Formation has been interpreted as part of a high-energy, low-latitude carbonate ramp (Aitken, 1997). The most basinward deposits are skeletal grainstone, wackestone and lime mudstone, which were probably deposited below fairweather wave-base. Shoreward deposits are coarse grainstone interfingered with high-energy sandstone.

A local unconformity delineates the top of the Gog Group in the area of Mount Stephen and Mount Field where the Peyto Formation is not present due to erosion related to flexure of the Kicking Horse Rim. In other areas, the contact between the Peyto and Mount Whyte Formation is disconformable (Aitken, 1996).

CONCLUSIONS

The Gog Group in the Bow Valley area comprises four Lower Cambrian units: (1) Fort Mountain Formation; (2) Lake Louise Formation; (3) St. Piran Formation; and (4) Peyto Formation. North of Bow Pass an additional unit, the Jasper Formation, occurs below the Fort Mountain Formation, related to accommodation created by active faulting during the latest Neoprotorozoic. In the Lake Louise and Lake O'Hara areas, four new members are proposed to subdivide the St. Piran Formation: (1) Lake O'Hara; (2) Lake Oesa; (3) Moraine Lake; and (4) Wiwaxy Peaks members.

A wide range of shallow-marine sub-environments is represented by purely siliciclastic facies. The Fort Mountain Formation records shallow-subtidal sedimentation during the initial phase of Early Cambrian transgression on the stabilized passive margin. The Lake Louise Formation gradationally overlies the Fort Mountain Formation, it was deposited in a protected low-energy inner-shelf setting regional maximum flooding event. The Lake O'Hara Member is a progradational unit on top of the Lake Louise Formation which records inner-shelf to shallow-subtidal compound dunes and sand sheets. The Lake Oesa Member is erosively based onto the Lake O'Hara Member and represents a tidal-flat deposited during a forced regression The Lake Oesa Member is capped by a transgressive shoreface, included now in lowermost part of the Moraine Lake Member. Inner-shelf sedimentation was dominant during deposition the middle part of this unit, followed by a return to shallow-subtidal conditions. Within this interval a depauperate trace-fossil suite reflects the influence of stress factors, such as salinity fluctuations and high flocculation rates, which could have been related to deltaic influence.

The contact between the Moraine Lake Member and the strata now included in the Wiwaxy Peaks Member represent a transgressive event. The uppermost member of the Wiwaxy Peaks Member records an inner-shelf sand-ridge complex, followed by a shoreface interval. The limestone-dominated Peyto Formation records deposition on a carbonate ramp that developed as ongoing transgression caused a decrease in siliciclastic sediment supply.

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Figure Captions

Figure 1: Geologic map of the Bow Valley region of the Rocky Mountains, western Canada showing the location of the studied outcrops. Mount Assiniboine is outside the map, 65 km southeast of Moraine Lake in the lower left of the map. Based on Geological Survey of Canada maps (Price and Mountjoy 1972a,b; 1978a,b; Price et al., 1980a,b)

Figure 2: Chronostratigraphy of Neoproterozoic and Lower Cambrian strata in the Rocky, Cariboo and central Purcell mountains. The basal conglomerate in Mount Assiniboine is provisionally placed in the Early Cambrian. Modified from Hein and McMechan (1994). Neoproterozoic=1000–542 Ma; Early Cambrian=542–513 Ma; Middle Cambrian=513–501 Ma (Robb et al., 2004; Shergold and Cooper 2004).

Figure 3: (A) Composite stratigraphic section of the Gog Group in Lake Louise and Lake O’Hara sector, with proposed new members. Legend as in figures 8 and 9. (B) Southern

side of Wiwaxy Peaks and Mount Huber at Lake O'Hara showing position of normal faults and stratigraphic subdivisions.

Figure 4: Mountainsides on the east side of the Bow Valley. (A) Southwestern flank of Redoubt Mountain. (B) Southeastern flank of Ptarmigan Peak. Fort Mountain Formation type section (51°29'37"N, 116°04'28"W; NAD 83; Map 82 N/8). (C) Southwestern flank of Castle Mountain.

Figure 5: Geologic map of the Lake O'Hara area. The intra-St. Piran unconformity detected by Desjardins et al. (2010) divides the lower from the upper St. Piran Formation.

Figure 6: Idealized bathymetric profile showing the main depositional settings recognized in the Gog Group.

Figure 7: Stratigraphic sections correlated between Mount Assiniboine (50°54'20"N, 115°38'43"W; Map 82 J/13), Lake O'Hara (51°21'26"N, 116°19'33"W; Map 82 N/8) and Cirque Lake (51°48'36"N, 116°38'03"W; Map 82 N/15). Legend as for Figures 8 and 9.

Figure 8: Stratigraphic sections and interpreted sedimentary environments. (A) Principal reference section of the Fort Mountain Formation at Lake O'Hara (51°21'26"N, 116°19'33"W; Map 82 N/8). (B) Type section of the Lake Louise Formation at Lake Louise (51°24'21"N, 116°13'57"W; Map 82 N/8). (C) Composite type section of the Lake O'Hara Member at Lake O'Hara, comprising two overlapping sections measured on the western flank of Yukness Mountain (51°21'11"N, 116°19'23"W; Map 82 N/8) and the southwestern edge of the Opabin Plateau beside Mary Lake (51°20'56"N, 116°19'47"W; Map 82 N/8). See Figure 11. Legend as for Figure 9. For more

information on the significance of sequence stratigraphic surfaces see Catuneanu et al. (2009).

Figure 9: Stratigraphic sections and interpreted sedimentary environments of Lake Oesa, Moraine Lake and Wiwaxy Peaks members (new) near Lake Oesa. (A) Type section of the Lake Oesa Member (51°21’25”N, 116°18’40”W; Map 82 N/8). (B) Reference section of the St. Piran Formation at Lake Oesa including proposed members and sedimentary environments (51°21’25”N, 116°18’40”W; Map 82 N/8). Legend as for Figure 8.

Figure 10: Jasper Formation at Cirque Lake. (A) Reference section on the southeastern flank of Mount Synge above Cirque Lake (51°48’36”N, 116°38’03”W; Map 82 N/15). (B) Sub-Cambrian unconformity between Neoproterozoic Jasper Formation and Early Cambrian Fort Mountain Formation (arrow). Person for scale. (C) Bed geometries characterised by lenticular-shaped, erosively based channel deposits (black arrows). White arrow marks the position of a laterally continuous purple-coloured interval. (D–G) Facies. (D) Pebble conglomerate (G_T) overlain in turn by thick-bedded set of thin- to medium-bedded trough cross-stratified, medium- to very coarse-grained pebbly sandstone (S_T) and very thick-bedded, planar cross-stratified, fine- to very coarse-grained sandstone (S_P). (E) Very thick-bedded set of amalgamated medium- to thick-bedded, trough cross-stratified, medium- to very coarse-grained sandstone (S_T) and sporadically intercalated planar laminated, fine- to medium-grained sandstone (S_L). (F) Medium-bedded, normally graded, medium- to very coarse-grained sandstone (S_G) with common rounded to subangular pebbles at the base. (G) Erosively based, medium-bedded, clast-supported pebble conglomerate (G_T) overlain by amalgamated, thick-bedded, normally graded, medium- to very coarse-grained sandstone (S_G).

Figure 11: Fort Mountain Formation. (A) Northeastern flank of Bow Peak. The contact between the Gog and Miette groups is a gentle angular unconformity (Aitken, 1969). (B) Reference section at Lake O'Hara (51°21'26"N, 116°19'33"W; Map 82 N/8). Arrow marks the contact between the Fort Mountain and Lake Louise formations. (C–G) Facies. (C) Conglomerate representing a transgressive lag at base of Fort Mountain Formation. Cirque Lake. (D) Amalgamated sets of medium- to thick-bedded, planar cross-stratified, medium-grained sandstone (S_{P1}) (FA-2). Lake Louise. (E) Medium-bedded, herringbone cross-stratified, fine- to medium-grained sandstone (S_{HGB}) (FA-2). Lake Louise. (F) Medium-bedded sets of planar cross-stratified (S_{P1}) and planar laminated (S_{L1}), fine- to medium-grained sandstone (FA-2). Black arrows mark bed boundaries. White arrows mark bedset boundary boundary contacts. Lake Louise. (G) Interbedded thin-bedded, trough cross-stratified (S_{T1}) and planar-laminated (S_{L1}) fine- to medium-grained sandstone with undulating liesegang bands (secondary) (lg) (FA-2). Lake Louise.

Figure 12: Lake Louise Formation. (A) Northeastern flank of Bow Peak. White arrows mark the lower and upper boundaries of the Lake Louise Formation. (B) Type section of the Lake Louise Formation on the northwestern flank of Fairview Mountain, near the western end of Lake Louise (51°24'21"N, 116°13'57"W; Map 82 N/8). Dashed lines mark boundary between the lower and upper units. (C–I) Facies. (C) Progradational interval composed of thick-bedded intercalated shale (M_S) and thin- to medium-bedded wavy- and lenticular-bedded, very fine-grained sandstone (H_1) (FA-4), overlain by intercalated thin-bedded flaser-, wavy- and lenticular-bedded, very fine-grained sandstone (H_1), with thin-bedded, rippled cross-laminated (S_{R2}) and planar-laminated (S_{L1}) very fine-grained sandstone and intensely bioturbated sandstone (S_{B2}) (FA-5). Top

of the progradational interval is marked by medium-bedded, planar-cross stratified, fine- to medium-grained sandstone (S_{P2}) (FA-6). Lake Louise. (D) FA-5 consisting of intercalated shale (M_S), very thinly interbedded sandstone and mudstone (H_1) and bioturbated sandstone (S_{B2}). Lake O'Hara. (E) Thin sandstone beds whose soles are disrupted by deep *Rusophycus* isp. burrows (*Ru*) (FA-5). Lake O'Hara. (F) Lenticular-bedded sandstone (H_1) overlain by a bioturbated sandtone (S_{B2}) containing large *Rusophycus* (*Ru*) (FA-5). Lake O'Hara. (G) Compacted layer below gutter cast (arrow) at the sole of sandstone bioturbated with *Rusophycus* isp. (S_{B2}) (FA-5). Lake O'Hara. (H) Thinly intercalated flaser-bedded (S_{F1}), planar laminated (S_{Ll}), micro-hummocky cross-stratified (S_{HCS2}) and bioturbated (S_{B2}) sandstone (FA-5). Lake O'Hara. (I) Slabbed surface of thick-laminated sandstone with intercalated thin mudstone laminae(H_1). *Te*=*Teichichnus rectus*. *Pl*=*Planolites* isp. (FA-5). Lake O'Hara. (J) Medium-bedded set of thin-bedded, planar cross-stratified sandstone internally containing thin mudstone laminae (arrows) (FA-6). Lake Louise.

Figure 13: Lake O'Hara Member, lower St. Piran Formation. (A) Northwestern flank of Fairview Mountain by Lake Louise. (B) Lower boundary at the type section. Lake Louise. (C–F) Facies. (C) Amalgamated, medium-bedded, planar cross-stratified fine- to medium-grained sandstone (S_{P3}) (FA-6) sharply overlain by very thin- to thin-bedded, intercalated ripple cross-laminated, fine- to very fine-grained sandstone and mudstone (H_2). Lake Louise. (D) Very thick-bedded set of planar cross-stratified sandstone (S_{P3}) (FA-6) preserving bedforms morphology on tops with mudstone laminae between and within beds overlain by intercalated thin bedded ripple cross-laminated sandstone (S_{R3}) and mudstone (M_2) representing dune bottomsets (FA-5). Lake Louise. (E) Set of fine- to

medium-grained sandstone within low-angle cross-stratification representing compound-dune deposits (S_{P3}) (FA-6) overlying intercalated ripple cross-laminated, fine- to very fine-grained sandstone and mudstone (H_2) (FA-5). Thin mudstone laminae occur between beds. Lake Louise. (F) Interval composed of laterally continuous amalgamated sets compound-dune deposits (FA-6). Compound dunes are represented by thickening- and coarsening-upward sets of thin- to medium-bedded, low-angle and planar cross-stratified, fine- to medium-grained sandstone (S_{P3}). Inclined and slightly erosive surfaces (arrows) separate different sets. Lake O'Hara.

Figure 14: Informal subdivisions in the Lake O'Hara Member, lower St. Piran Formation at Lake O'Hara. (A) West side of cliff approximately 200 m high at Lake Yukness. (B) Cliff approximately 160 m high at base of Mary Lake.

Figure 15: Facies of Lake O'Hara Member. (A) Thick-bedded, compound cross-stratified, fine- to medium-grained sandstone (S_{P3}) (FA-6) showing sigmoidal-shaped surfaces (black arrows) separating different cross-stratified beds. Lake O'Hara. Hammer length equals 35 cm. (B) Thin- to medium-bedded mudstone (M_2) between ripple cross-laminated sandstone (S_{R3}) and thin-bedded planar cross-stratified (S_{P3}) of FA-6. Lake O'Hara. (C) Intercalated flaser-bedded (S_{F2}), ripple-cross laminated sandstone and mudstone (H_2) of FA-7. White arrow points to gutter cast. Lake O'Hara. (D) Bioturbated mudstone (M_2) and flaser-bedded sandstone (S_{F2}) of FA-7. *Te*=*Teichichnus rectus*. *Pl*=*Planolites* isp. Sy=shrinkage crack. Lake O'Hara. (E) Vertical transition from wavy-bedded and rippled cross-laminated sandstone (H_2) of FA-7 to sandstone pipe rock (Pr) of FA-8, caped by non-bioturbated plane-laminated sandstone (S_{P3}). Lake O'Hara. (F) Dense *Skolithos linearis* assemblage (Pr) (FA-8). Lake Louise. (G) Amalgamated

medium- to thick-bedded, planar cross-stratified sandstone (S_{P4}) (FA-9). Lake O'Hara. (H) Tabular to lenticular, medium- to thick-bedded cross-stratified sandstone (FA-2) containing large *S. linearis*. Lake O'Hara.

Figure 16: Lake Oesa, Moraine Lake and Wiwaxy Peaks members. (A) Type section of Moraine Lake Member on the western side of Tower of Babel by Moraine Lake (51°19'38"N, 116°10'37"W; Map 82 N/8). (B–C) Regressive surfaces of marine erosion (RSME) between the Lake O'Hara and the Lake Oesa members (intra-St. Piran unconformity). (B) Lake Oesa. (C) Lake Louise. (D) Type section of Lake Oesa Member on western side of cliff mostly below Lake Oesa. (E) Reference section of St. Piran Formation on southern flank of Mount Huber near Lake Oesa. (F) Reference section of Wiwaxy Peaks Member on western flank of Mount Temple above Moraine Lake (51°19'49"N, 116°12'50"W; Map 82 N/8).

Figure 17: Lake Oesa and Moraine Lake members. (A–E) Lake Oesa Member. (A) Thin- to medium-bedded planar and trough cross-stratified, fine- to coarse-grained sandstone, locally containing mud drapes and chips (S_X) (FA-10). Hammer length is 35 cm. Lake Louise. (B) Mudstone bedding plane with polygonal desiccation cracks. Lake Oesa. (C) Mudstone bedding plane with desiccation cracks. Lake Oesa. (D) Fining-upward interval composed of thin- bedded, planar cross-stratified, fine-grained sandstone (S_X) overlain by intercalated very thin- to thin-bedded ripple cross-laminated very fine- to fine-grained sandstone and mudstone (H_3). Lake Oesa. (E) Interference ripples in mudstone (H_3). Lake Oesa. (F) Hummocky cross-stratified sandstone (S_{HCS4}) (FA-11) sharply overlain by very thin- to thin-bedded, intercalated very fine- to fine-grained sandstone and mudstone (H_4) of FA-12. Above Lake Oesa. (G) Erosional surface (white arrow) within heterolithic

cross-stratified, very fine- to fine-grained sandstone and mudstone (FA-12). Lake Oesa. (H) Medium- to thick-bedded, sigmoidal-shaped, cross-stratified sandstone with asymptotic foresets which grade to horizontal ripple cross-laminated bottomsets (S_{SIG2}). Abundantly present are bundles, reactivation surfaces, mud drapes (FA-12). Lake Oesa. (I) Convolute bedding consisting of syn-sedimentary fold (FA-12). Opabin Plateau.

Figure 18: Moraine Lake Member. (A) Southern flank of Mount Huber, by Lake Oesa. Person for scale inside ellipse. (B) Sharp contact (black arrow) between very thin- to thin-bedded, intercalated very fine- to fine-grained sandstone and mudstone (H_4) (FA-12) and thin- to medium-bedded, fine- to medium-grained sandstone (S_{T4}) (FA-14). Mount Huber. (C) Thickening- and coarsening-upward parasequence comprising lenticular-bedded sandstone and massive mudstone intercalated with ripple cross- and planar laminated sandstone (He_5) and thin- to medium-bedded cross-stratified sandstone (S_{P3}) (FA-15). Mount Huber. (D) Very thick-bedded trough cross-stratified sandstone (S_{T5}). Lake Louise. (E) Thick tabular beds of planar cross-stratified, fine- to medium-grained sandstone (S_{P4}) (FA-2). Highway #1, near Sink Lake.

Figure 19: Wiwaxy Peaks Member. (A–D) Highway #1 near Spiral Tunnels. (A) Very thick-bedded compound cross-stratified sandstone package. White lines mark its overall lenticular geometry. (B) Interval composed of very thick-bedded planar and trough cross-stratified sandstone showing bipolar paleocurrent indicators. Person for scale. (C) Portion of very thick-bedded compound cross-stratified sandstone interval showing transition (white arrow) from intercalated very thin- to thin-bedded sandstone and mudstone to medium-bedded cross-stratified sandstone. (D) Coarsening- and thickening-upward amalgamated hummocky cross-stratified sandstone. (E) Very thick-bedded, lenticular,

cross-stratified sandstone characterised by bundles, reactivation surfaces (white arrows), mud drapes, and asymptotic foresets which grade to horizontal, rippled bottomsets. Mount Temple above Moraine Lake.

Figure 20: Southern flank of Mount Huber, Lake O'Hara. Contact between Peyto and Mount Whyte formations corresponds to the Lower–Middle Cambrian boundary.

Figure 21: Mount Assiniboine. (A) Southeastern side of Sunburst Peak. White line marks unconformity between the Gog Group and Middle Cambrian Naiset Formation. (B) Unconformity between the Miette and Gog groups. Near Gog Lake, Mount Assiniboine. (C) Very thick-bedded, pebble and cobble conglomerate sharply overlain by very thin-bedded mudstone and followed by cross-stratified sandstone. TS=transgressive surface. (D) Southeastern side of Sunburst Peak showing intercalated fine- to very fine-grained sandstone and shale, similar to facies of the Lake Louise Formation. (E) Uppermost Gog Group on the southeastern side of Sunburst Peak. White arrow marks shift from coarsening-upward to fining-upward trend. Strata above the arrow are red.

Figure 22: Paleoenvironmental evolution of the inner part of the broad continental shelf recorded by the Gog Group in the area of Bow Valley. Rifting was followed by a change from a braided fluvial setting to a shallow-marine environment. The inner shelf experienced transgression and a series of progradational events until siliciclastic sediment supply ceased and the setting became dominated by carbonate sediment.

Table Captions

Table 1: Facies of the Fort Mountain Formation.

Table 2: Facies of the Lake Louise Formation.

Table 3: Facies of the Lake O'Hara Member, lower St. Piran Formation.

Table 4: Facies of the Lake Oesa and Moraine Lake members, upper St. Piran Formation.

FACIES	LITHOLOGY & SEDIMENTARY STRUCTURES	DEPOSITIONAL PROCESSES	FACICIES ASSOCIATIONS	SEDIMENTARY ENVIRONMENTS
S_{HCS1} Hummocky cross-stratified sandstone	Erosionally based, medium- to thick-bedded, hummocky and low-angle cross-stratified, very well-sorted, very fine- to fine-grained sandstone. Local internal erosional surfaces.	High energy; bed-load deposition and suspension fall-out due to storm and wave action.	FA–2	Shallow subtidal
S_{M1} Structureless sandstone	Tabular, thin- to medium-bedded, well-sorted, very fine- to medium-grained sandstone; appears structureless.	Low to moderate energy; bed-load deposition under lower-flow regime. Structureless aspect probably due to uniformity in grain size.	FA–1, 2	Shallow subtidal
S_{HGB} Herringbone cross-stratified sandstone	Tabular beds, thin- to medium-bedded, herringbone cross-stratified, well sorted, fine- to medium-grained sandstone.	Moderate- to high-energy; bed-load deposition as two superimposed 2D dunes migrating in opposite directions.	FA–2	Shallow subtidal
S_{SIG1} Sigmoidal-shaped cross-stratified sandstone	Sigmoidal-shaped cross-stratified, well-sorted, medium- to coarse-grained sandstone. Sharp and erosive bases; sharp or gradational tops. Abundant mudstone laminae between thin-bedded foresets which merge tangentially into horizontal bottom-sets.	Moderate energy; bed-load deposition as 2D compound dunes during periods of weaker current activity and mud deposition.	FA–3	Inner shelf
S_{B1} Bioturbated sandstone	Homogenized and cross-stratified, fine- to medium-grained sandstone with abundant *Skolithos linearis.*	Bedforms colonized by *Skolithos linearis*.	FA–3	Shallow subtidal to inner shelf
S_{CON} Convolute sandstone	Thin- to medium-bedded convolute-laminated, well-sorted, fine- to medium-grained sandstone.	Soft-sediment deformation due to earthquakes.	FA–2	Shallow subtidal
S_{R1} Ripple cross-laminated sandstone	Very thin- to thin-bedded current-ripple cross-laminated, very well-sorted, very fine- to medium-grained sandstone. No mudstone flasers.	Low to moderate energy; bed-load deposition as small bedforms (current and wave ripples).	FA–1, 2	Shallow subtidal to inner shelf
S_{P1} Planar cross-stratified sandstone	Tabular bodies, thin- to thick-bedded planar and low-angle cross-stratified, very well- to moderately sorted, medium- to very coarse-grained sandstone with local granules.	Moderate to high energy; bed-load deposition as 2D dunes.	FA–2	Shallow subtidal
S_{T1} Trough cross-stratified sandstone	Thin- to thick-bedded, trough cross-stratified, well- to moderately sorted, medium- to very coarse-grained sandstone with local granules.	Moderate to high energy; bed-load deposition as 3D dunes.	FA–2	Shallow subtidal
S_{L1} Planar laminated sandstone	Thin-bedded planar laminated, very well-sorted, very fine- to fine-grained sandstone.	Low to moderate energy; bed-load deposition under lower-flow regime.	FA–1, 2	Shallow subtidal to inner shelf
Slt Siltstone	Very thin-bedded, laminated siltstone.	Low energy; suspension fallout.	FA–1, 2	Shallow subtidal to inner shelf
M_1 Mudstone	Very thin-bedded, laminated mudstone.	Low energy; suspension fallout.	FA–3	Inner shelf

FACIES	LITHOLOGY & SEDIMENTARY STRUCTURES	DEPOSITIONAL PROCESSES	FACIES ASSOCIATIONS	SEDIMENTARY ENVIRONMENTS
S_{HCS2} Hummocky cross-stratified sandstone	Erosionally based, thin-bedded, hummocky and low-angle cross-stratified, very well-sorted, fine grained sandstone. Local internal erosional surfaces and rippled tops. Rare vertical trace fossils (BI 1–2). Abundant horizontal and sub-horizontal trace fossils at soles. Local syneresis cracks.	High energy; bed-load deposition and suspension fall-out due to storm and wave action.	FA–5	Inner shelf
H_1 Lenticular- and wavy-bedded sandstone	Intercalated very thin- to thin-bedded, very fine-grained sandstone and laminated mudstone. Local planar and ripple cross-lamination. Preserved as 30–100 cm thick heterolithic packages. Commonly horizontal and sub-horizontal trace fossils and syneresis cracks.	Low energy; suspension fall-out and episodic deposition. Alternation of current or wave action and slack-water periods.	FA–4, 5	Outer to inner shelf
M_S Shale	Very thin-bedded, laminated shale. Commonly horizontal and sub-horizontal trace fossils.	Low energy; suspension fallout.	FA–4	Outer shelf
S_{P2} Planar cross-stratified sandstone	Medium- to thick-bedded bedsets of lenticular, planar cross-stratified fine- to medium-grained sandstone. Mudstone laminae between beds constituting the bedsets. Foresets which merge into horizontal very thin- to thin-bedded bottom-sets. Rare trace fossils at soles.	Moderate energy; bed-load deposition as 2D dunes during periods of weaker current activity and mud deposition. Lenticular aspect of beds reflects sand starvation.	FA–6	Inner shelf
S_{L2} Planar laminated sandstone	Thin-bedded, planar laminated, very well-sorted, very fine-grained sandstone.	Low to moderate energy; bed-load deposition under lower flow regime.	FA–5	Inner shelf
S_{B2} Burrowed sandstone	Cross-stratified, very fine- to fine-grained sandstone containing vertical trace fossils (BI 1–2). Rare horizontal and sub-horizontal trace fossils at soles.	Moderate energy; bed-load deposition as dunes and ripples colonized by *Skolithos, Diplocraterion,* and/or *Rosselia* producers.	FA–6	Inner shelf
S_{B3} Bioturbated sandstone	Highly bioturbated (BI 5–6), very fine- to fine-grained sandstone. Abundant horizontal and sub-horizontal trace fossils at soles.	Episodic sand deposition in low-energy areas of the inner shelf and colonization mainly by a deposit-feeding fauna.	FA–5	Inner shelf
S_{F1} Flaser-bedded sandstone	Very well-sorted, very fine-grained flaser-bedded sandstone. Wave and current rippled lamina sets separated by very thin- to thin-bedded lamina sets.	Low to moderate energy; bed-load deposition as small bedforms (wave and current ripples). Suspension fall-out deposition of fine-grained particles during low-energy periods (i.e. slack water). Mudstone flasers and laminae suggest tidal current effects.	FA–5	Inner shelf
S_{R2} Ripple cross-laminated sandstone	Lenticular to wavy, very thin- to thin-bedded, ripple cross-laminated, very well-sorted, very fine-grained sandstone. Local mudstone laminae. Scattered horizontal trace fossils at bed soles.	Low to moderate energy; bed-load deposition as small bedforms (current and wave ripples).	FA–5	Inner shelf

FACIES	LITHOLOGY & SEDIMENTARY STRUCTURES	DEPOSITIONAL PROCESSES	FACIES ASSOCIATIONS	SEDIMENTARY ENVIRONMENTS
H_2 Lenticular- and wavy-bedded sandstone	Intercalated very thin- to thin-bedded, very fine- to fine-grained sandstone and thinly laminated mudstone. Local planar and ripple cross lamination. 5–30 cm thick heterolithic packages.	Low energy; suspension fall-out and episodic sand deposition. Alternation of current or wave action and slack-water periods.	FA–5, 7, 8, 9	Inner shelf
S_{R3} Ripple cross-laminated sandstone	Medium-bedded packages of 2–10 cm thick, ripple cross-laminated very fine- to fine-grained sandstone separated by very thin mudstone laminae. Laterally and vertically transitions to trough cross-stratified sandstone. Current-ripple cross-laminated, very well-sorted, very fine- to medium-grained sandstone.	Low to moderate energy; bed-load deposition as small bedforms (current and wave ripples).	FA–5, 8	Inner shelf
S_{F2} Flaser-bedded sandstone	Very thin- to thin-bedded, very well-sorted, flaser-bedded, very fine-grained sandstone forming 10–100 cm thick packages. Wave- and current-rippled lamina sets separated by very thin- to thin-bedded laminae.	Low to moderate energy; bed-load deposition as small bedforms (wave and current ripples). Suspension fall-out deposition of fine-grained particles during low-energy periods (i.e. slack water). Mudstone flasers and laminae suggest tidal currents effects.	FA–7, 8	Inner shelf
S_{T2} Trough cross-stratified sandstone	Medium- to thick-bedded sets of 10–30 cm thick, trough cross-stratified, very well- to moderately sorted, fine- to medium-grained sandstone. Locally associated with facies S_R.	Moderate to high energy; bed-load deposition as small 3D dunes. Mudstone laminae indicate suspension fall-out during slack-water periods. Mudstone intraclasts suggest erosion of previously deposited cohesive mud.	FA–8	Inner shelf
S_{T3} Trough cross-stratified sandstone	Thick-bedded, erosionally based, trough cross-stratified, medium- to very coarse-grained sandstone. Local mud drapes and mudstone intraclasts.	Moderate to high energy; bed-load deposition of small- to medium-sized 3D dunes.	FA–9, 2	Shallow subtidal to inner shelf
S_{P3} Planar cross-stratified sandstone	Medium-bedded, tabular bodies, planar and low-angle cross-stratified, very well-sorted and fine- to medium-grained sandstone. Local mud drapes.	Moderate to high energy; bed-load deposition of medium-sized 2D dunes.	FA–6, 8	Inner shelf
S_{P4} Planar cross-stratified sandstone	Thick-bedded, sharp-based tabular bodies, planar and low-angle cross-stratified, very well- to moderately sorted, medium- to very coarse-grained sandstone.	Moderate to high energy; bed-load deposition of large-sized 2D dunes.	FA–9, 2	Shallow subtidal to inner shelf
S_{HCS3} Hummocky cross-stratified sandstone	Thick-bedded, erosionally based, hummocky and low-angle cross-stratified, very well-sorted, fine- to very fine-grained sandstone. Local internal erosional surfaces and gutter casts.	High energy; bed-load deposition and suspension fall-out due to storm and wave action.	FA–7, 8, 9	Shallow subtidal to inner shelf
S_{L3} Planar laminated sandstone	Thin-bedded, planar laminated, very well-sorted, very fine-grained sandstone.	Low to moderate energy; bed-load deposition under lower-flow regime.	FA–5, 7	Shallow subtidal to inner shelf
S_{M2} Structureless sandstone	Medium- to thick-bedded, tabular, well-sorted, medium- to coarse-grained sandstone. Appears structurless	Low to moderate energy; bed-load deposition under lower-flow regime. Structurless aspect probably related to uniformity in grain size.	FA–8	Shallow subtidal to inner shelf
Pr *Skolithos* pipe rock	Medium- to very thick-bedded, intensively bioturbated (BI 4–5), very fine- to medium-grained sandstone. Local very thin to thin discontinuous laminae. Vertical trace fossils dominant.	Moderate energy, episodic sand sedimentation. Multiple colonization events by suspension-feeding animals.	FA–8	Shallow subtidal to inner shelf

M_2 Massive mudstone	Thin- to medium-bedded mudstone. Appears structurless.	Low energy; high sedimentation rates of flocculated fluid mud.	FA–5	Inner shelf

FACIES	LITHOLOGY & SEDIMENTARY STRUCTURES	DEPOSITIONAL PROCESSES	FACIES ASSOCIATIONS	SEDIMENTARY ENVIRONMENTS
S_X Cross-stratified sandstone	Erosively to sharp-based, planar and trough cross-stratified, moderately sorted, fine- to medium-grained sandstone. Scattered mudstone intraclasts. Common intercalated ripple cross-laminated sandstone and mud drapes. Scattered *Skolithos linearis*.	Moderate to high energy; bed-load deposition as 3D and 2D dunes. Mudstone laminae indicate suspension fall-out deposition during slack-water periods. Mudstone intraclasts suggest erosion of previously deposited mudstone.	FA–10	Tidal-flat complex
H_3 Lenticular-, wavy- and flaser-bedded sandstone	Very thin- to thin-bedded, very fine- to fine-grained sandstone intercalated with very thin- to medium lamina of mudstone. Common interference ripples, wrinkle marks and desiccation cracks. Scattered shallow-tier horizontal trace fossils.	Low to moderate energy; bed-load deposition of small bedforms (wave and current ripples). Suspension fall-out of fine-grained particles during low-energy periods (i.e. slack water). Mudstone flasers and laminae, and bipolar currents suggest tidal currents.	FA–10	Tidal-flat complex
H_4 Lenticular-, wavy- and flaser-bedded sandstone	Very thin- to thin-bedded, intercalated very fine- to fine grained-sandstone and mudstone. Local inclined heterolithic stratification (IHS). Scattered thin-bedded BCD turbidites.	Low to moderate energy; bed-load deposition of small bedforms (wave and current ripples). Suspension fall-out deposition of fine-grained particles during low-energy periods (i.e. slack water). Mudstone flasers and laminae, and biplolar paleocurrent patterns suggest currents of tidal origin. IHS represents point bars in low-energy channels. Thin bedded turbidites formed due concentrated flows in an estuary.	FA–12	Prodelta-like
H_5 Lenticular-, wavy- and flaser-bedded sandstone	Intercalated very thin- to thin-bedded, very fine- to fine-grained sandstone and mudstone. Common syneresis cracks and graded beds. Local *Planolites* isp.	low to moderate energy**.** Massive mudstone represents fluid muds, under high-floculation rates. Sandstone deposited at the toes of the delta-front. Graded beds formed due to episodic concentrated flows.	FA–15	Prodelta-like
S_{HCS4} Hummocky cross-stratified sandstone	Erosionally based, thin- to medium-bedded, hummocky and low-angle cross-stratified, very well-sorted, fine-grained sandstone.	High energy; bed-load and suspension fall-out deposition due to storm and wave action.	FA–11	Shoreface
S_{L4} Planar laminated sandstone	Very thin- to thin-bedded, planar laminated very fine-grained sandstone and siltstone. Locally few very thin to thin lamina of mudstone. Locally *Bergaueria* isp.	Low to moderate energy. Fair-weather suspension fall-out and lower-regime planar laminated sandstone.	FA–11	Shoreface
S_{SIG2} Sigmoidal cross-stratified sandstone	Lenticular, medium- to thick-bedded, sigmoidal-shaped, cross-stratified sandstone with asymptotic foresets which grade to horizontal ripple bottom sets. Abundant bundles, reactivation surfaces, and mud drapes.	High energy; bed-load deposition as 2D dunes during periods of weaker currents and mud deposition. Reactivation surfaces due to tidal currents.	FAs–12, 13	Prodelta-like–shallow subtidal
S_{P3} Planar cross-stratified sandstone	Erosively to sharp-based, medium-bedded, fine- to coarse-grained sandstone. Commonly intercalated with thin- to medium-bedded sandstones within coarsening- and thickening-upwards cycles.	Moderate to high energy; bed-load deposition as 2D dunes.	FA–15	Shallow subtidal
S_{P4} Planar cross-stratified sandstone	Tabular, thin- to thick-bedded, planar cross-stratified, very well- to moderately sorted, fine- to medium-grained sandstone.	Moderate to high energy; bed-load deposition as 2D dunes.	FA–16	Shallow subtidal

S_{T4} Trough cross-stratified sandstone	Erosively to sharp-based, thin- to medium-bedded, fine- to medium-grained sandstone. Common undulating tops.	Moderate to high energy; bed-load deposition as 3D dunes.	FA–14	Shoreface
S_{T5} Trough cross-stratified sandstone	Erosively to sharp-based, medium- to very thick-bedded, fine- to coarse-grained sandstone. Commonly intercalated with thin- to medium-bedded sandstones within coarsening- and thickening-upwards cycles.	High energy; bed-load deposition as 3D dunes.	FA–15	Shallow subtidal

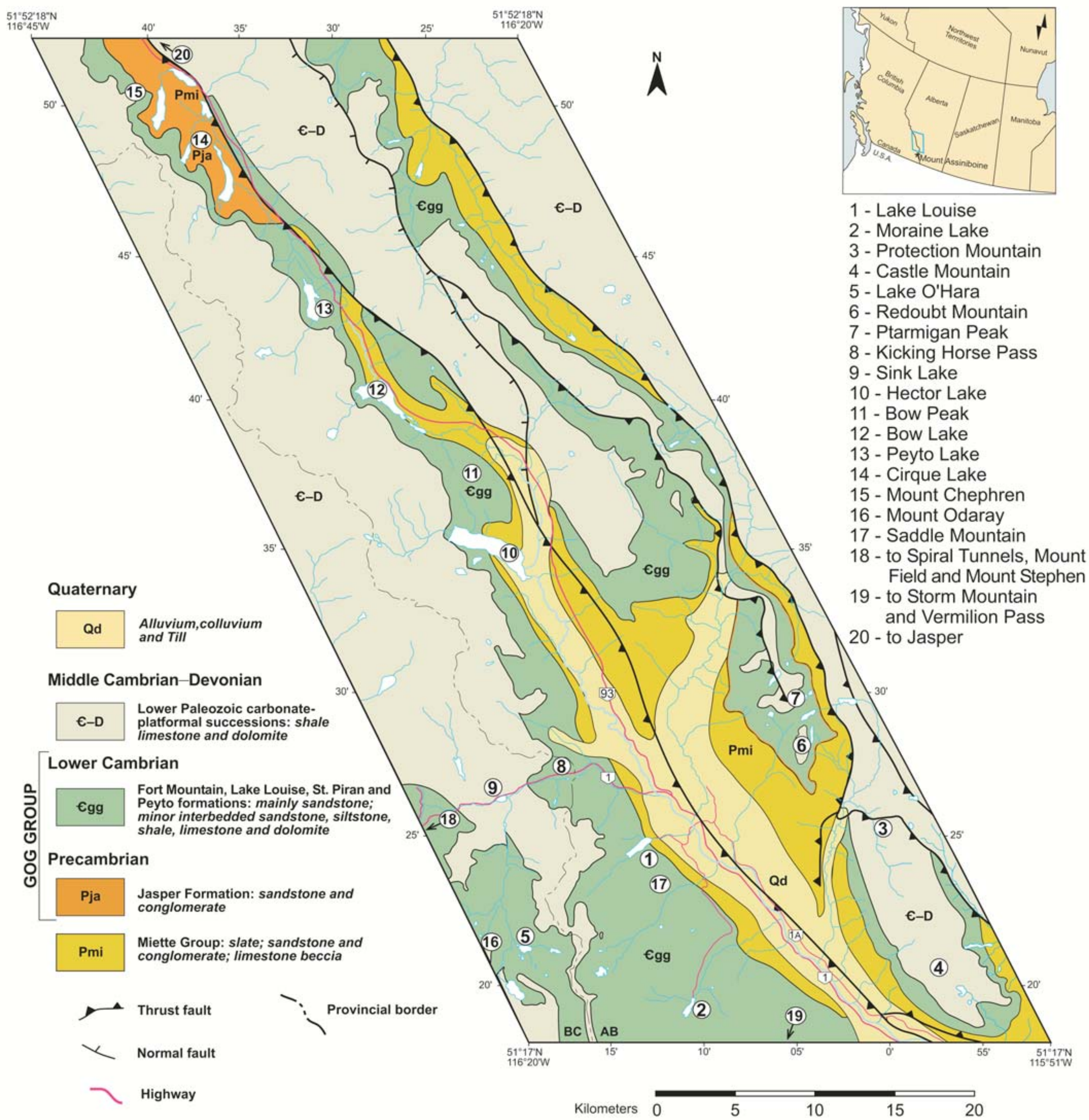
51°52'18"N 116°45'W
51°52'18"N 116°20'W
Yukon
Northwest Territories
Nunavut
British Columbia
Alberta
Saskatchewan
Manitoba
Canada
U.S.A.
Mount Assiniboine
1 - Lake Louise
2 - Moraine Lake
3 - Protection Mountain
4 - Castle Mountain
5 - Lake O'Hara
6 - Redoubt Mountain
7 - Ptarmigan Peak
8 - Kicking Horse Pass
9 - Sink Lake
10 - Hector Lake
11 - Bow Peak
12 - Bow Lake
13 - Peyto Lake
14 - Cirque Lake
15 - Mount Chephren
16 - Mount Odaray
17 - Saddle Mountain
18 - to Spiral Tunnels, Mount Field and Mount Stephen
19 - to Storm Mountain and Vermilion Pass
20 - to Jasper
Quaternary
Qd
Alluvium, colluvium and Till
Middle Cambrian–Devonian
Є–D
Lower Paleozoic carbonate-platformal successions: shale limestone and dolomite
GOG GROUP
Lower Cambrian
Єgg
Fort Mountain, Lake Louise, St. Piran and Peyto formations: mainly sandstone; minor interbedded sandstone, siltstone, shale, limestone and dolomite
Precambrian
Pja
Jasper Formation: sandstone and conglomerate
Pmi
Miette Group: slate; sandstone and conglomerate; limestone beccia
Thrust fault
Provincial border
Normal fault
Highway
BC
AB
51°17'N 116°20'W
51°17'N 115°51'W
Kilometers 0 5 10 15 20

Figure 1

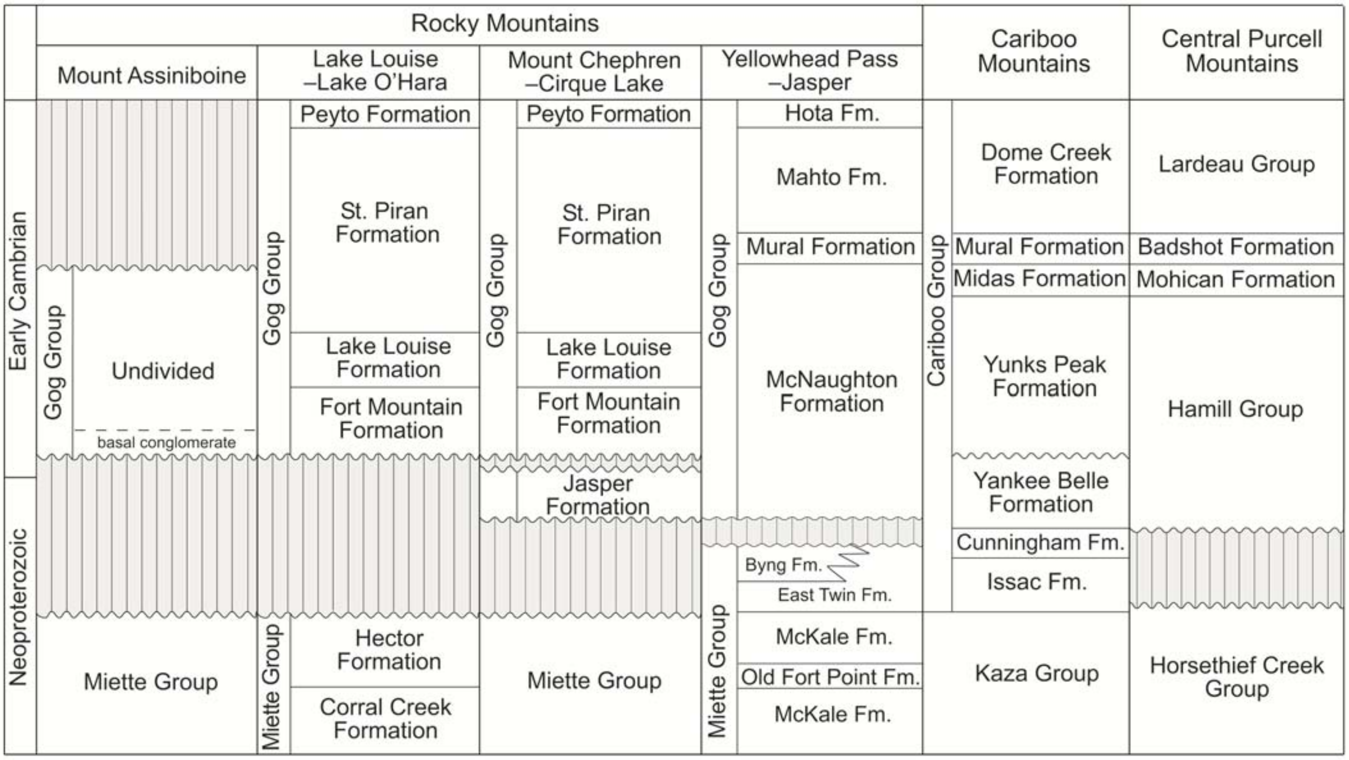
Rocky Mountains
Mount Assiniboine
Lake Louise –Lake O'Hara
Mount Chephren –Cirque Lake
Yellowhead Pass –Jasper
Cariboo Mountains
Central Purcell Mountains
Early Cambrian
Neoproterozoic
Gog Group
Undivided
basal conglomerate
Miette Group
Peyto Formation
St. Piran Formation
Lake Louise Formation
Fort Mountain Formation
Hector Formation
Corral Creek Formation
Jasper Formation
Hota Fm.
Mahto Fm.
Mural Formation
McNaughton Formation
Byng Fm.
East Twin Fm.
McKale Fm.
Old Fort Point Fm.
Cariboo Group
Dome Creek Formation
Midas Formation
Yunks Peak Formation
Yankee Belle Formation
Cunningham Fm.
Issac Fm.
Kaza Group
Lardeau Group
Badshot Formation
Mohican Formation
Hamill Group
Horsethief Creek Group

Figure 2

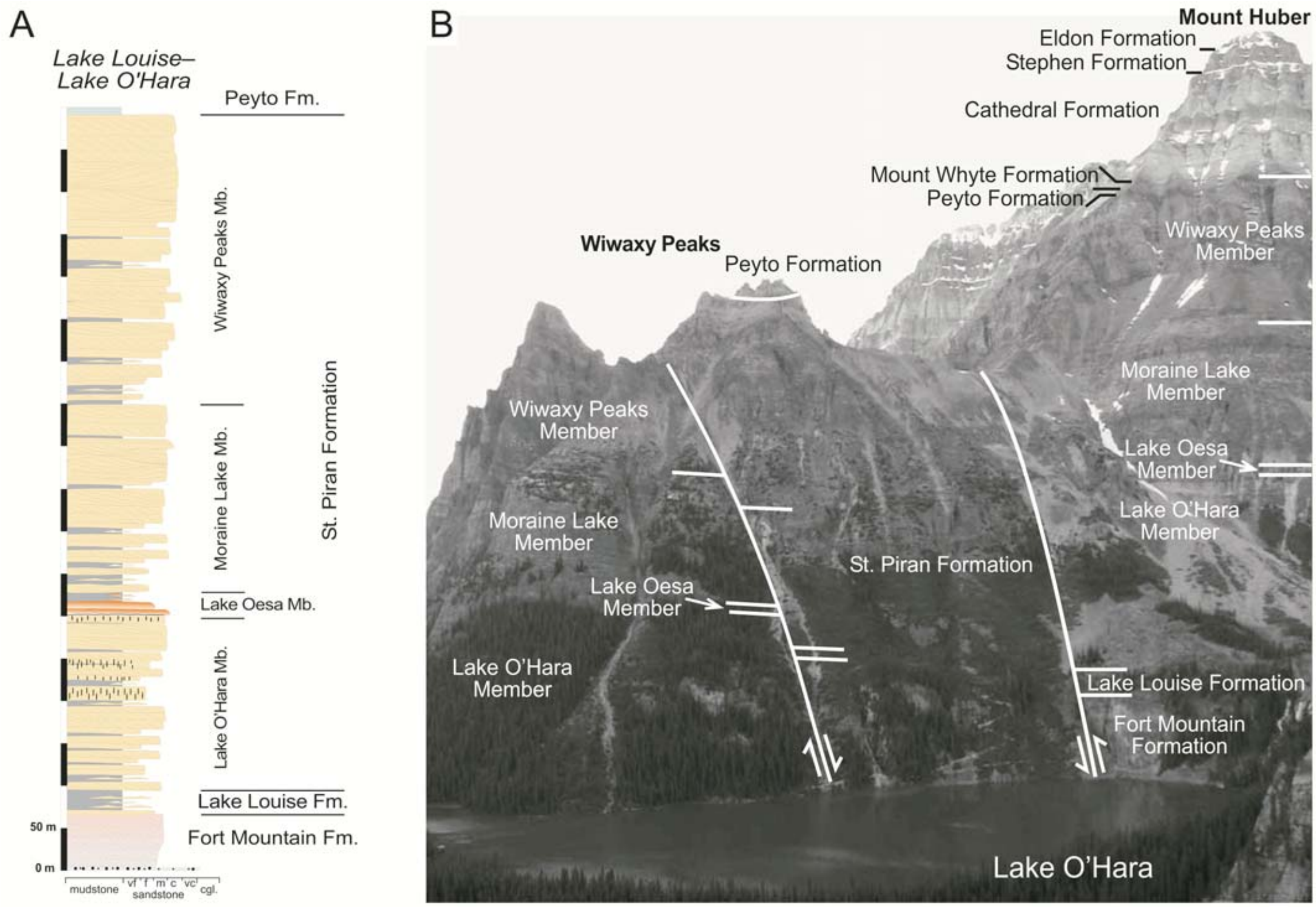
A
Lake Louise–
Lake O'Hara
Peyto Fm.
Wiwaxy Peaks Mb.
Moraine Lake Mb.
Lake Oesa Mb.
Lake O'Hara Mb.
St. Piran Formation
Lake Louise Fm.
Fort Mountain Fm.
50 m
0 m
mudstone
vf f m c vc
sandstone
cgl.
B
Mount Huber
Eldon Formation
Stephen Formation
Cathedral Formation
Mount Whyte Formation
Peyto Formation
Wiwaxy Peaks
Peyto Formation
Wiwaxy Peaks Member
Moraine Lake Member
Lake Oesa Member
Lake O'Hara Member
St. Piran Formation
Wiwaxy Peaks Member
Moraine Lake Member
Lake Oesa Member
Lake O'Hara Member
Lake Louise Formation
Fort Mountain Formation
Lake O'Hara

Figure 3

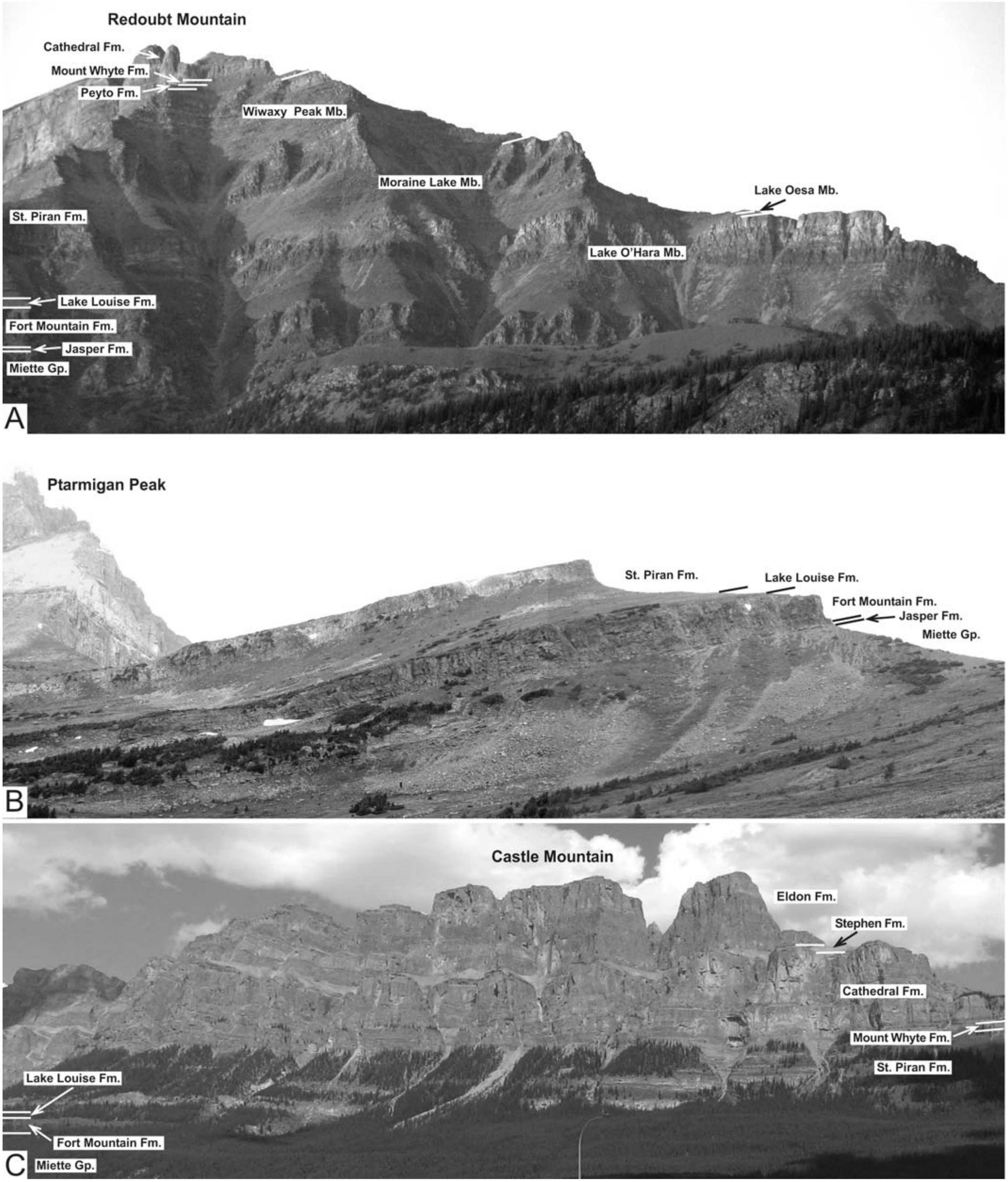
Redoubt Mountain
Cathedral Fm.
Mount Whyte Fm.
Peyto Fm.
Wiwaxy Peak Mb.
Moraine Lake Mb.
Lake Oesa Mb.
St. Piran Fm.
Lake O'Hara Mb.
Lake Louise Fm.
Fort Mountain Fm.
Jasper Fm.
Miette Gp.
A
Ptarmigan Peak
St. Piran Fm.
Lake Louise Fm.
Fort Mountain Fm.
Jasper Fm.
Miette Gp.
B
Castle Mountain
Eldon Fm.
Stephen Fm.
Cathedral Fm.
Mount Whyte Fm.
St. Piran Fm.
Lake Louise Fm.
Fort Mountain Fm.
C
Miette Gp.

Figure 4

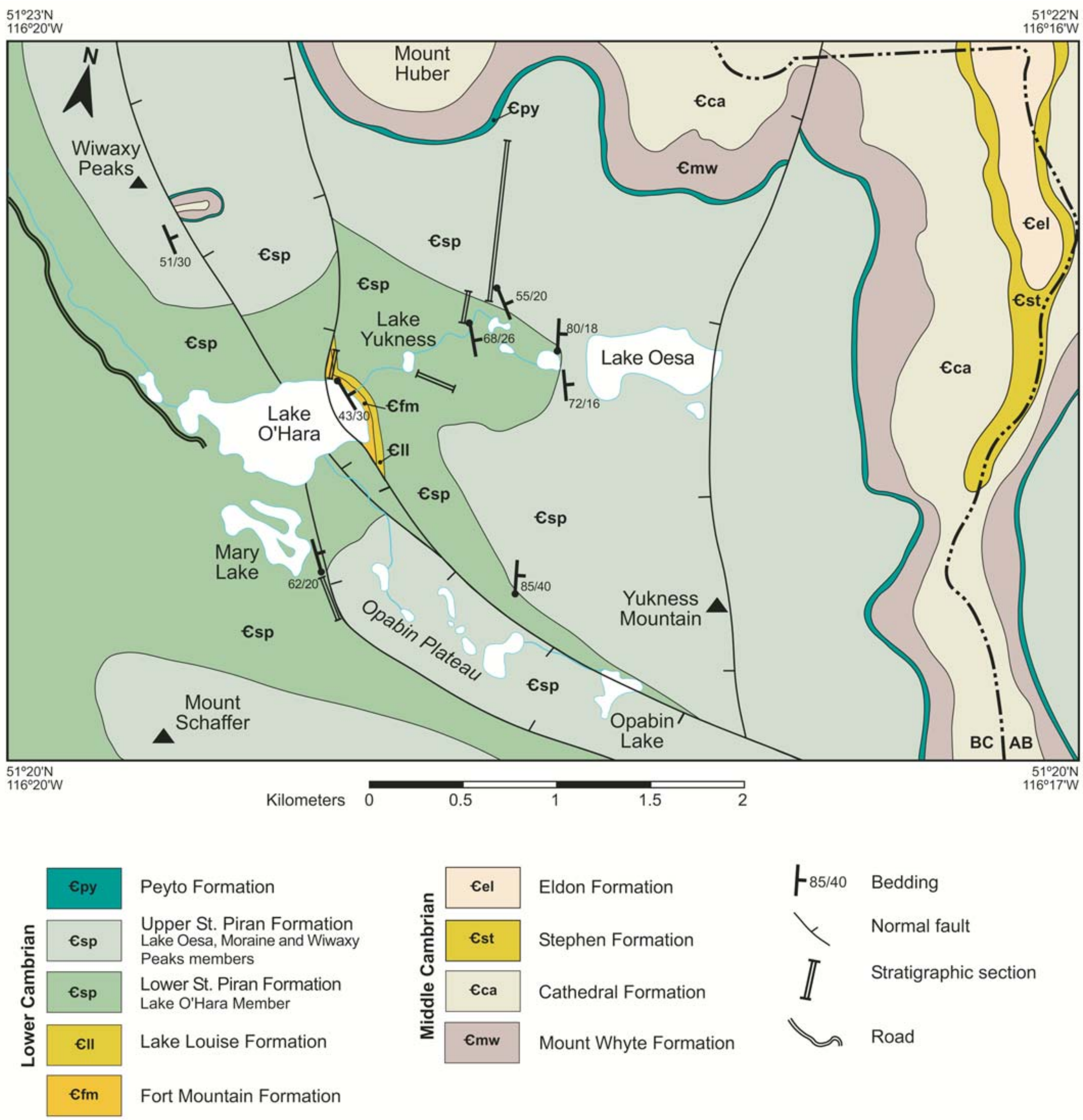
51°23'N
116°20'W
51°22'N
116°16'W
N
Mount
Huber
Ꞓpy
Ꞓca
Ꞓmw
Wiwaxy
Peaks
51/30
Ꞓsp
Ꞓsp
Ꞓsp
55/20
Lake
Yukness
68/26
80/18
Lake Oesa
Ꞓsp
72/16
Lake
O'Hara
43/30
Ꞓfm
Ꞓll
Ꞓsp
Ꞓsp
Ꞓel
Ꞓst
Ꞓca
Mary
Lake
62/20
85/40
Yukness
Mountain
Ꞓsp
Opabin Plateau
Ꞓsp
Mount
Schaffer
Opabin
Lake
BC
AB
51°20'N
116°20'W
51°20'N
116°17'W
Kilometers
0
0.5
1
1.5
2
Lower Cambrian
Ꞓpy Peyto Formation
Ꞓsp Upper St. Piran Formation
Lake Oesa, Moraine and Wiwaxy Peaks members
Ꞓsp Lower St. Piran Formation
Lake O'Hara Member
Ꞓll Lake Louise Formation
Ꞓfm Fort Mountain Formation
Middle Cambrian
Ꞓel Eldon Formation
Ꞓst Stephen Formation
Ꞓca Cathedral Formation
Ꞓmw Mount Whyte Formation
85/40 Bedding
Normal fault
Stratigraphic section
Road

Figure 5

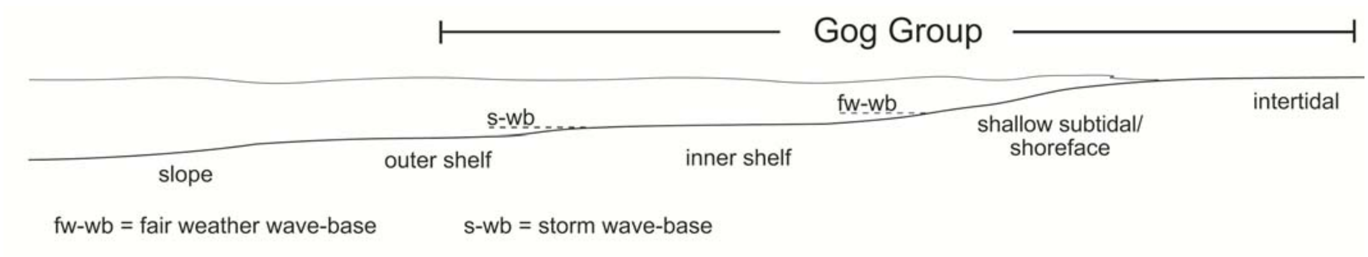
Gog Group
s-wb
fw-wb
intertidal
shallow subtidal/
shoreface
slope
outer shelf
inner shelf
fw-wb = fair weather wave-base
s-wb = storm wave-base

Figure 6

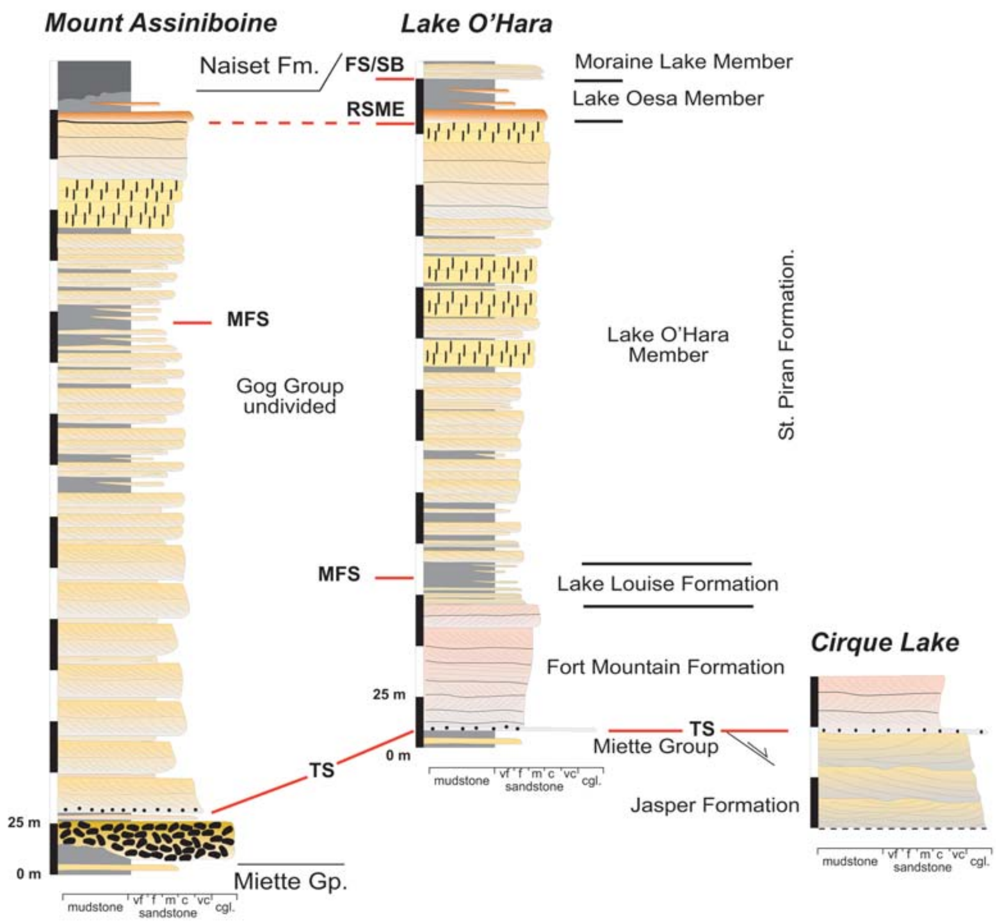
Mount Assiniboine
Lake O'Hara
Cirque Lake
Naiset Fm.
FS/SB
RSME
Moraine Lake Member
Lake Oesa Member
MFS
Gog Group
undivided
Lake O'Hara
Member
St. Piran Formation.
MFS
Lake Louise Formation
Fort Mountain Formation
25 m
TS
0 m
Miette Group
TS
Jasper Formation
25 m
0 m
Miette Gp.
mudstone
vf f m c vc
sandstone
cgl.
mudstone
vf f m c vc
sandstone
cgl.
mudstone
vf f m c vc
sandstone
cgl.

Figure 7

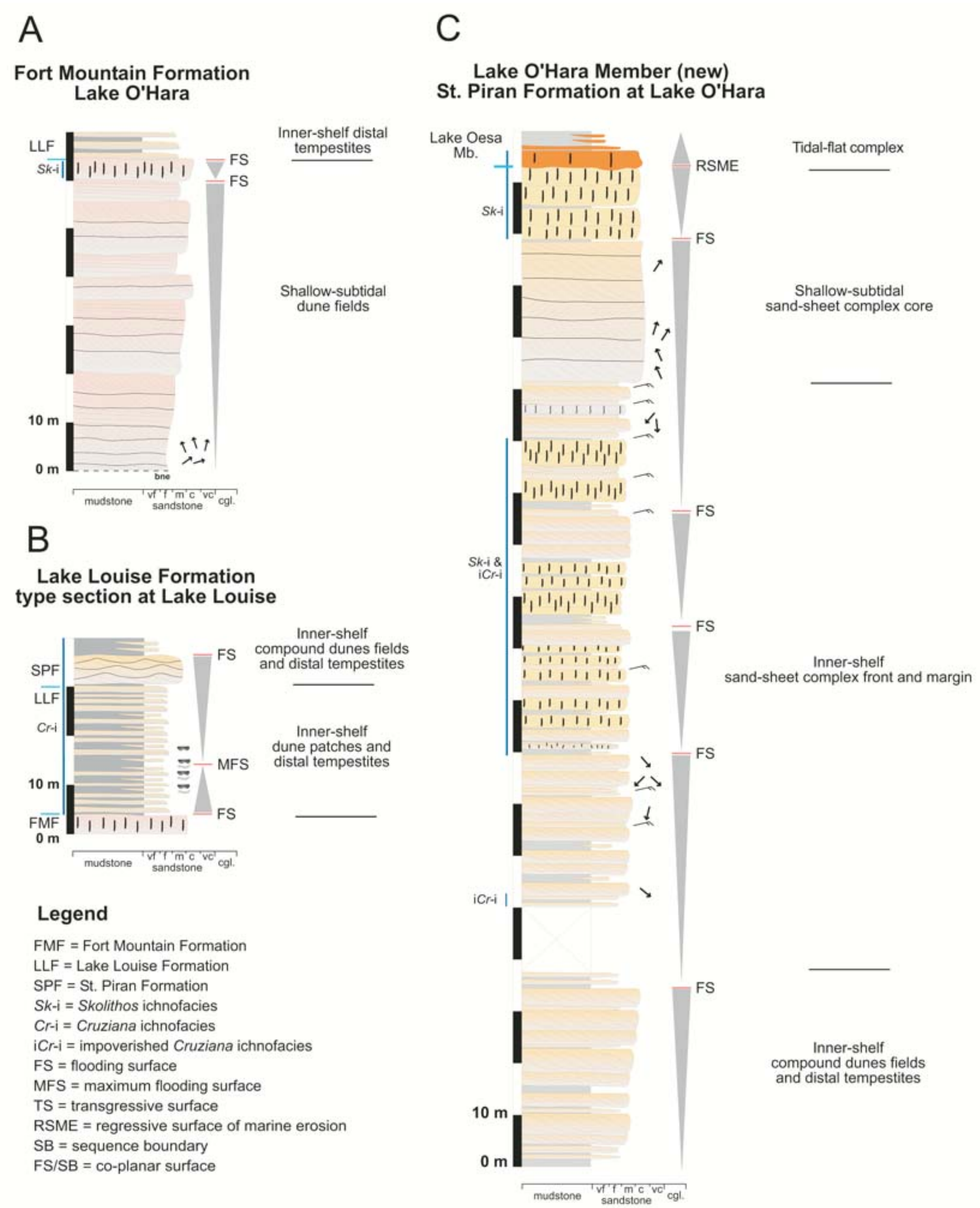
A
Fort Mountain Formation
Lake O'Hara
LLF
Sk-i
FS
FS
Inner-shelf distal tempestites
Shallow-subtidal dune fields
10 m
0 m
bne
mudstone
vf f m c vc
sandstone
cgl.
B
Lake Louise Formation
type section at Lake Louise
SPF
LLF
Cr-i
10 m
FMF
0 m
FS
MFS
FS
Inner-shelf compound dunes fields and distal tempestites
Inner-shelf dune patches and distal tempestites
Legend
FMF = Fort Mountain Formation
LLF = Lake Louise Formation
SPF = St. Piran Formation
Sk-i = Skolithos ichnofacies
Cr-i = Cruziana ichnofacies
iCr-i = impoverished Cruziana ichnofacies
FS = flooding surface
MFS = maximum flooding surface
TS = transgressive surface
RSME = regressive surface of marine erosion
SB = sequence boundary
FS/SB = co-planar surface
C
Lake O'Hara Member (new)
St. Piran Formation at Lake O'Hara
Lake Oesa Mb.
Sk-i
RSME
FS
FS
FS
FS
FS
Tidal-flat complex
Shallow-subtidal sand-sheet complex core
Sk-i & iCr-i
Inner-shelf sand-sheet complex front and margin
iCr-i
Inner-shelf compound dunes fields and distal tempestites
10 m
0 m

Figure 8

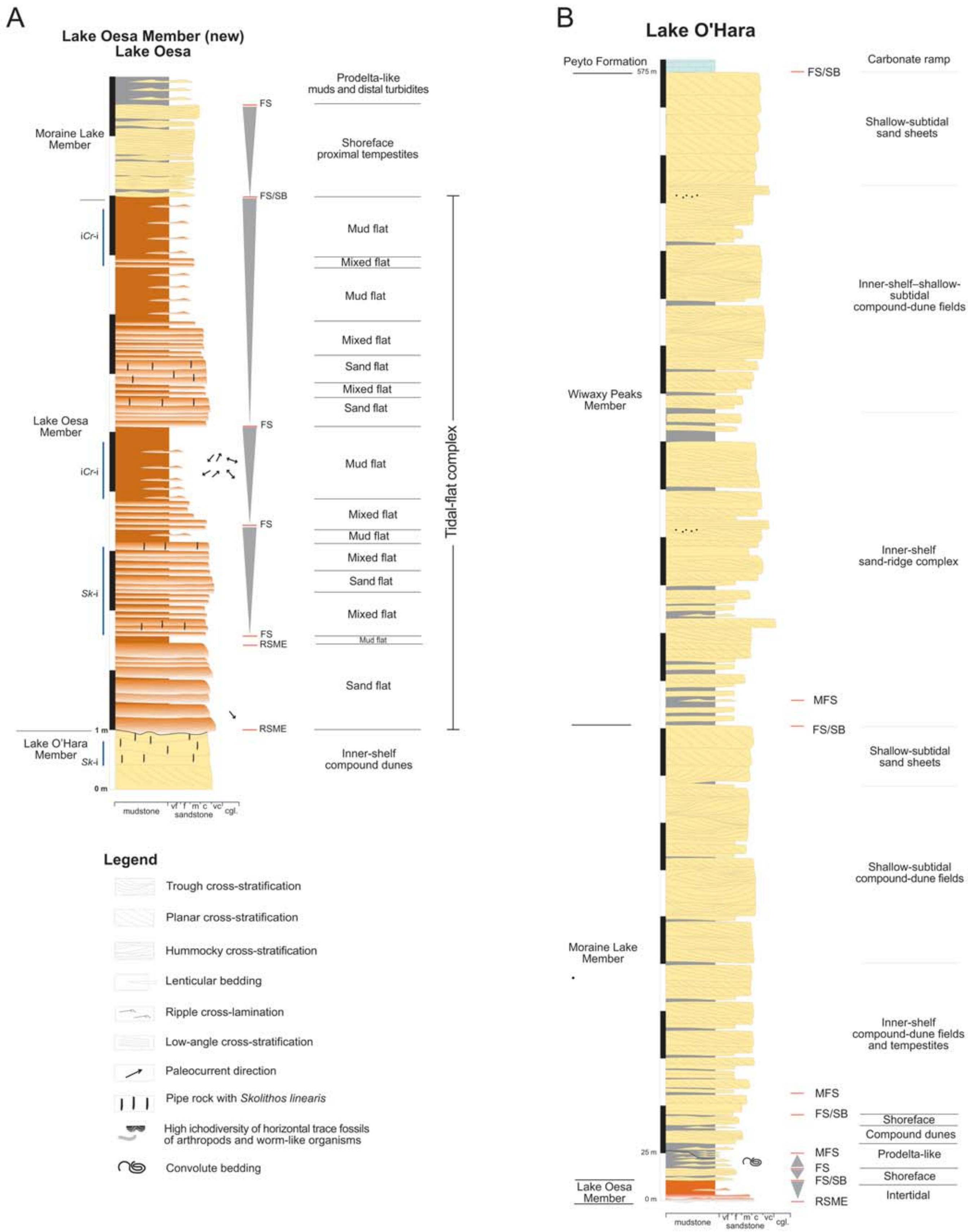
A
Lake Oesa Member (new)
Lake Oesa
Prodelta-like muds and distal turbidites
Shoreface proximal tempestites
Moraine Lake Member
Lake Oesa Member
Lake O'Hara Member
FS
FS/SB
RSME
Mud flat
Mixed flat
Sand flat
Inner-shelf compound dunes
Tidal-flat complex
mudstone
sandstone
cgl.
Legend
Trough cross-stratification
Planar cross-stratification
Hummocky cross-stratification
Lenticular bedding
Ripple cross-lamination
Low-angle cross-stratification
Paleocurrent direction
Pipe rock with Skolithos linearis
High ichodiversity of horizontal trace fossils of arthropods and worm-like organisms
Convolute bedding
B
Lake O'Hara
Peyto Formation
575 m
Carbonate ramp
Shallow-subtidal sand sheets
Inner-shelf–shallow-subtidal compound-dune fields
Wiwaxy Peaks Member
Inner-shelf sand-ridge complex
MFS
Shallow-subtidal compound-dune fields
Moraine Lake Member
Inner-shelf compound-dune fields and tempestites
Shoreface
Compound dunes
Prodelta-like
Intertidal
25 m
0 m
Lake Oesa Member

Figure 9

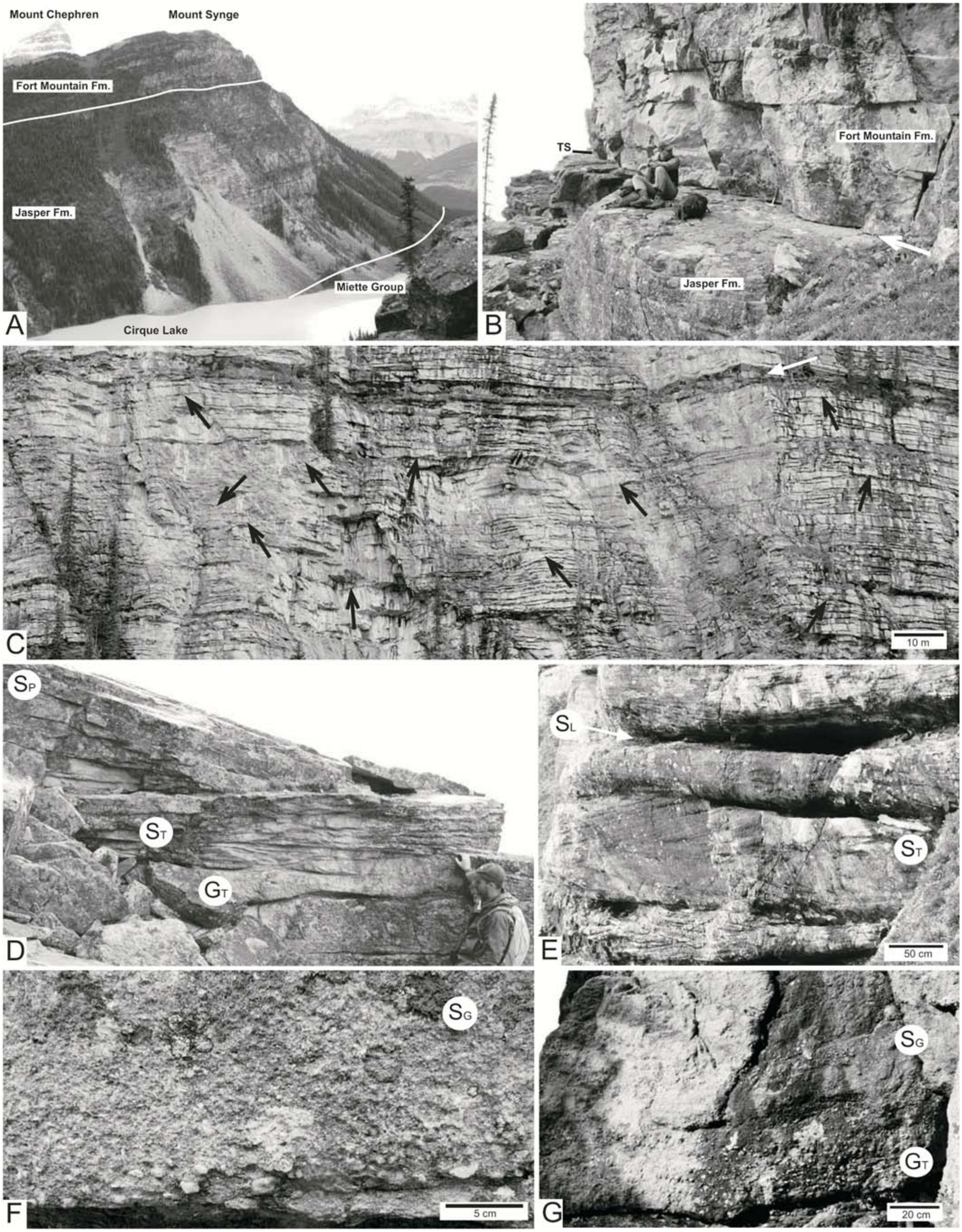
Mount Chephren
Mount Synge
Fort Mountain Fm.
Jasper Fm.
Miette Group
Cirque Lake
A
TS
Fort Mountain Fm.
Jasper Fm.
B
C
10 m
SP
ST
GT
D
SL
ST
E
50 cm
SG
F
5 cm
SG
GT
G
20 cm

Figure 10

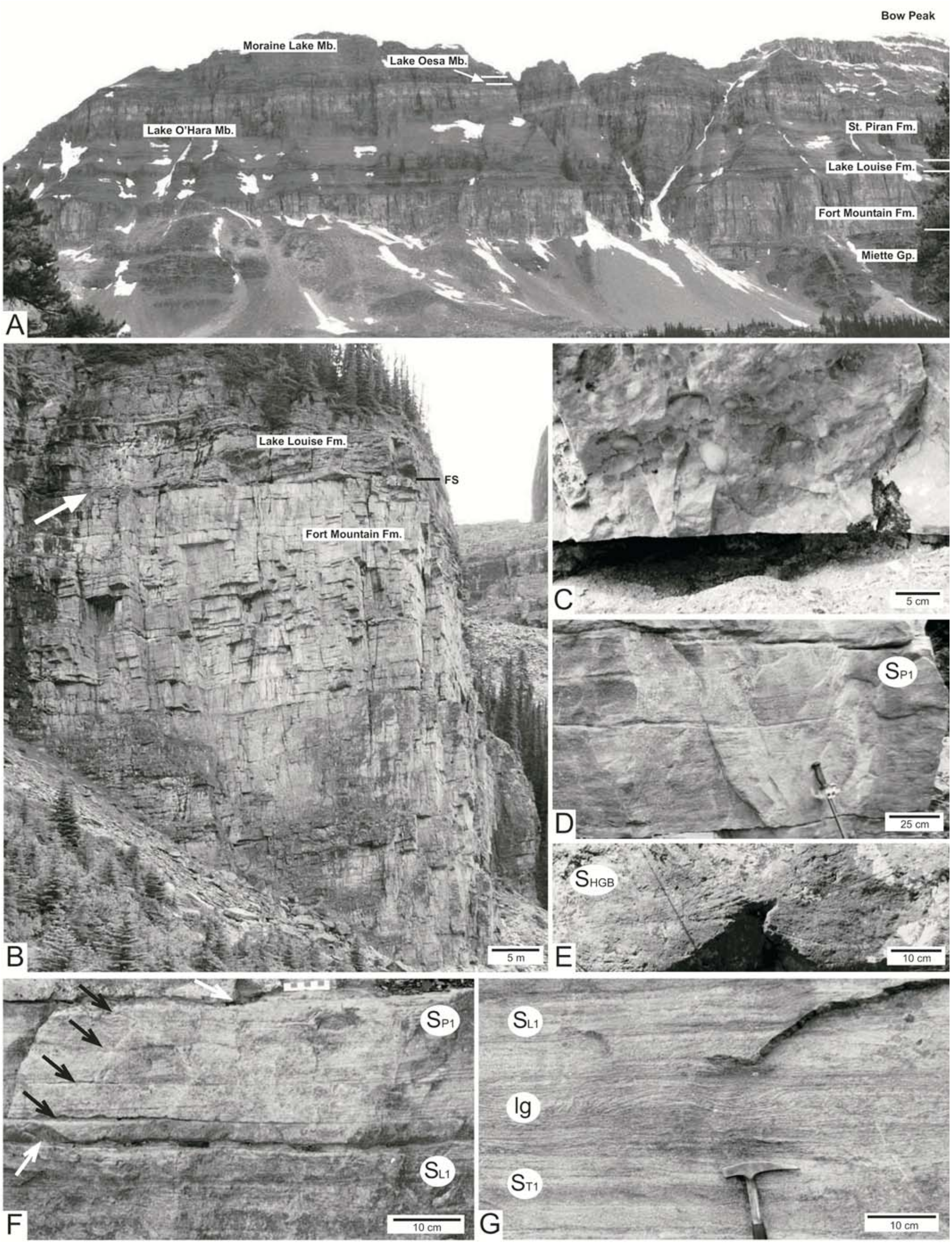
Bow Peak
Moraine Lake Mb.
Lake Oesa Mb.
Lake O'Hara Mb.
St. Piran Fm.
Lake Louise Fm.
Fort Mountain Fm.
Miette Gp.
A
Lake Louise Fm.
FS
Fort Mountain Fm.
5 m
B
5 cm
C
S_{P1}
25 cm
D
S_{HGB}
10 cm
E
S_{P1}
S_{L1}
10 cm
F
S_{L1}
lg
S_{T1}
10 cm
G

Figure 11

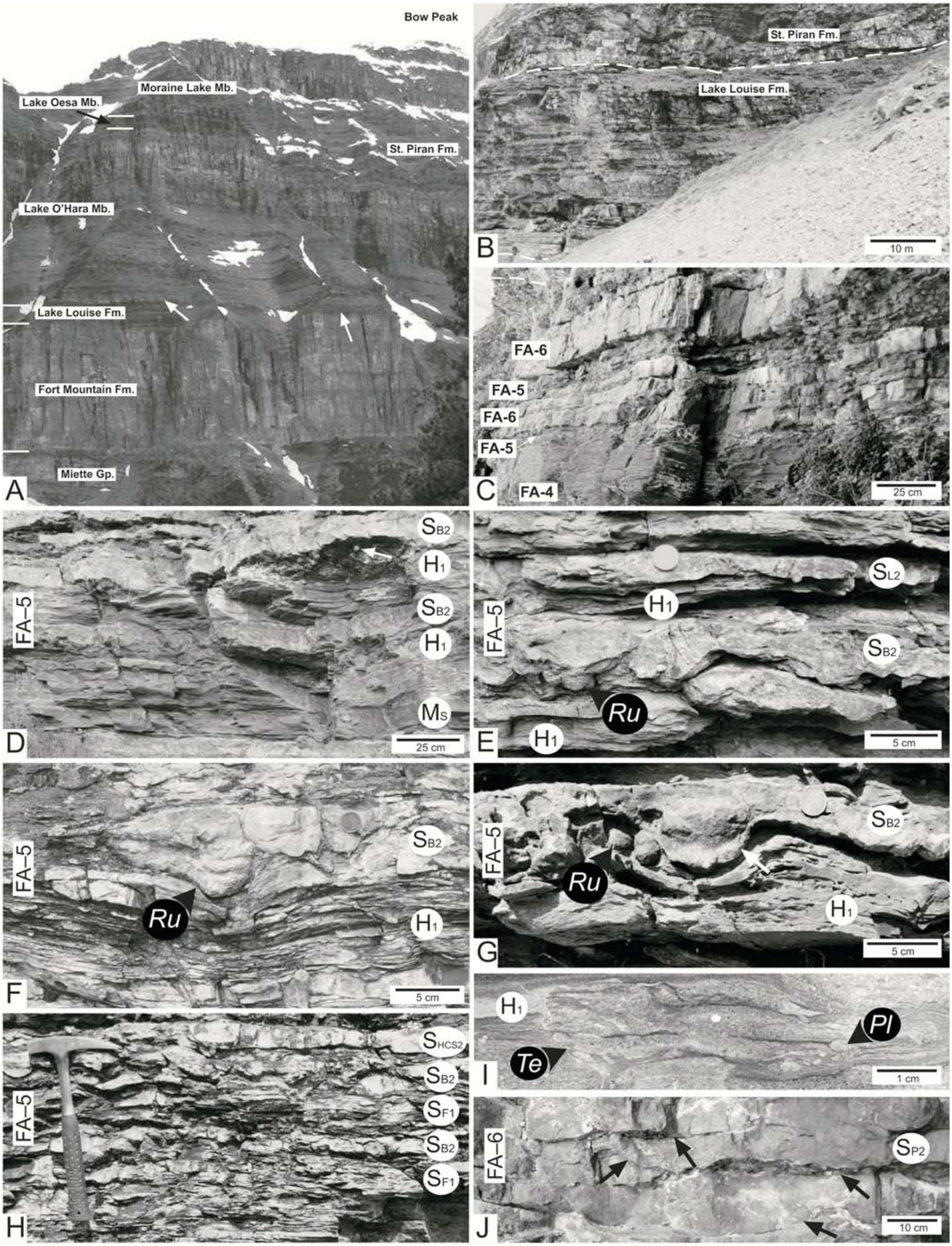
Bow Peak
Moraine Lake Mb.
Lake Oesa Mb.
St. Piran Fm.
Lake O'Hara Mb.
Lake Louise Fm.
Fort Mountain Fm.
Miette Gp.
A
St. Piran Fm.
Lake Louise Fm.
10 m
B
FA-6
FA-5
FA-6
FA-5
FA-4
25 cm
C
S_{B2}
H_1
S_{B2}
H_1
M_S
FA–5
25 cm
D
S_{L2}
H_1
S_{B2}
Ru
H_1
FA–5
5 cm
E
S_{B2}
FA–5
Ru
H_1
5 cm
F
S_{B2}
FA–5
Ru
H_1
5 cm
G
S_{HCS2}
S_{B2}
S_{F1}
S_{B2}
S_{F1}
FA–5
H
H_1
Pl
Te
1 cm
I
FA–6
S_{P2}
10 cm
J

Figure 12

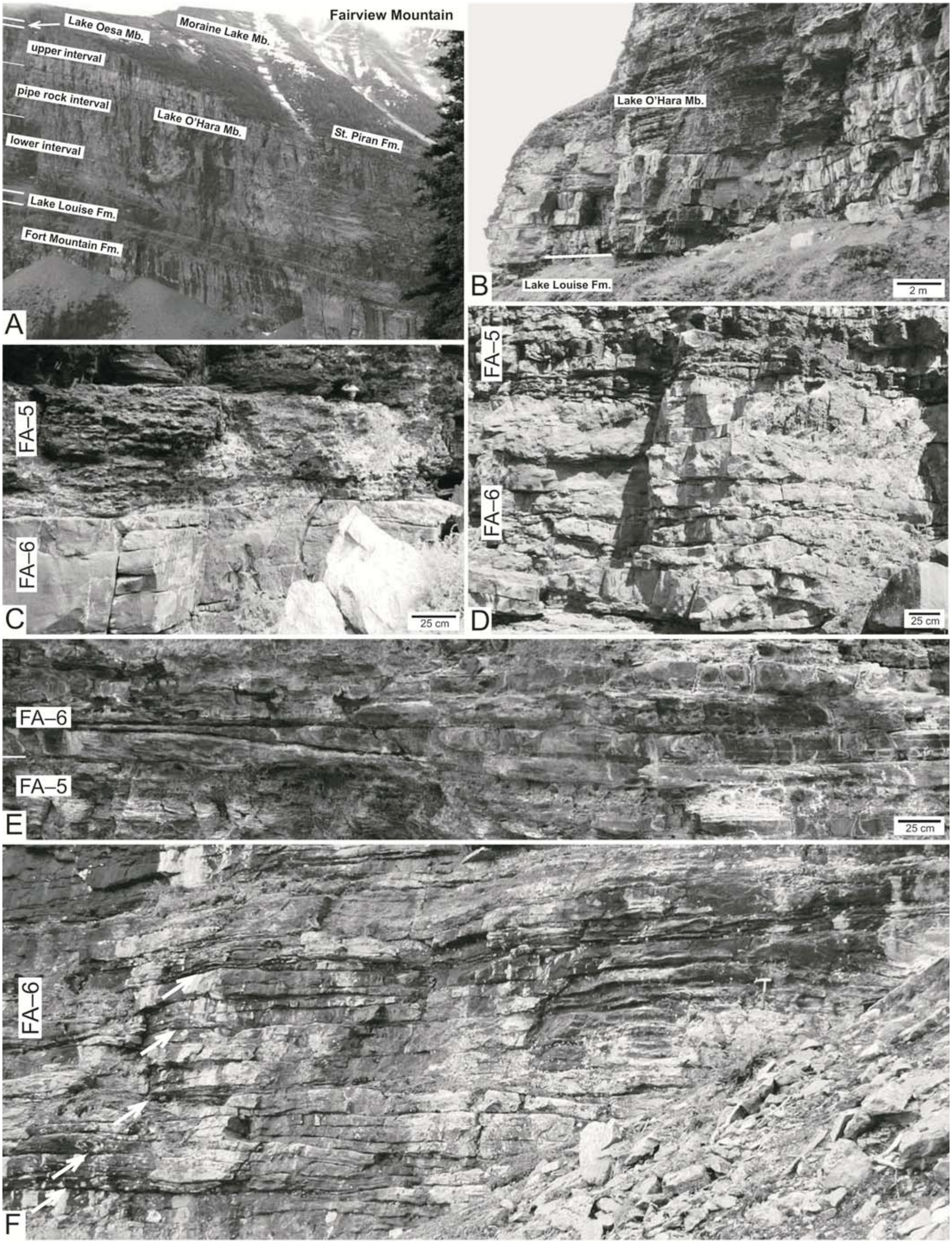
Fairview Mountain
Lake Oesa Mb.
Moraine Lake Mb.
upper interval
pipe rock interval
Lake O'Hara Mb.
St. Piran Fm.
lower interval
Lake Louise Fm.
Fort Mountain Fm.
A
Lake O'Hara Mb.
B
Lake Louise Fm.
2 m
FA–5
FA–6
C
25 cm
FA–5
FA–6
D
25 cm
FA–6
FA–5
E
25 cm
FA–6
F

Figure 13

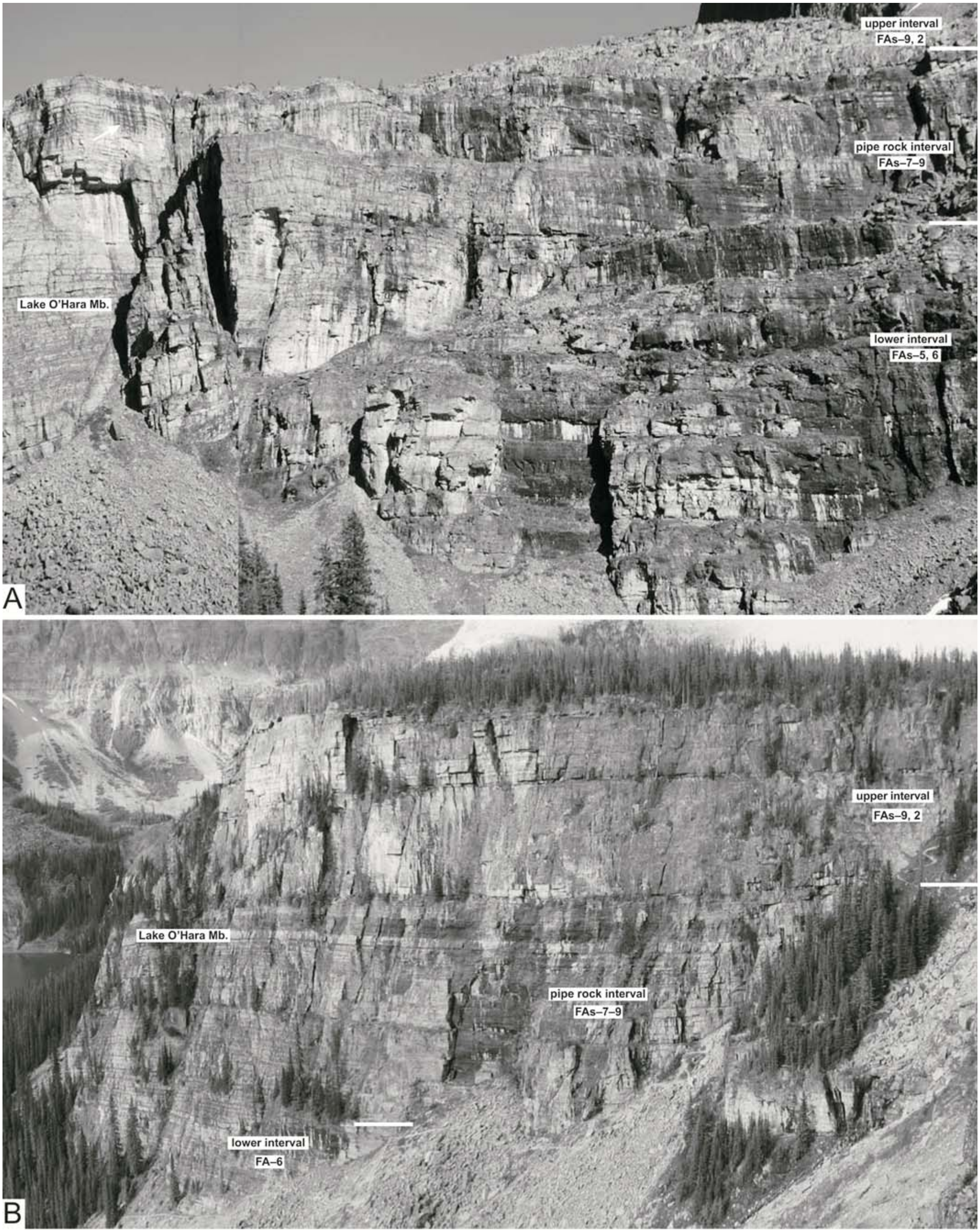
upper interval
FAs–9, 2
pipe rock interval
FAs–7–9
Lake O'Hara Mb.
lower interval
FAs–5, 6
A
upper interval
FAs–9, 2
Lake O'Hara Mb.
pipe rock interval
FAs–7–9
lower interval
FA–6
B

Figure 14

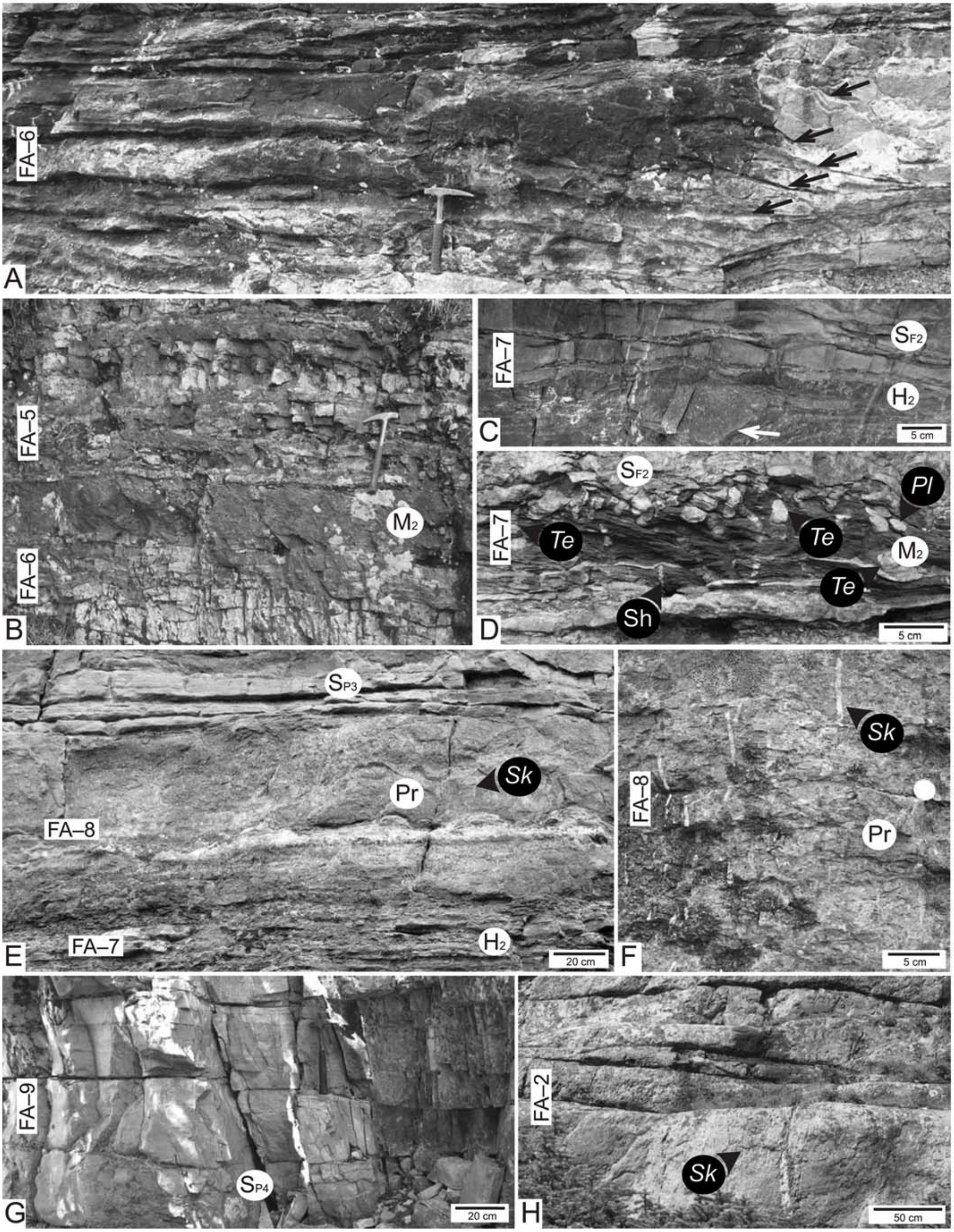
FA–6
A
FA–5
M2
FA–6
B
FA–7
SF2
H2
5 cm
C
SF2
Pl
FA–7
Te
Te
M2
Te
Sh
5 cm
D
SP3
Sk
Pr
FA–8
FA–7
H2
20 cm
E
Sk
FA–8
Pr
5 cm
F
FA–9
SP4
20 cm
G
FA–2
Sk
50 cm
H

Figure 15

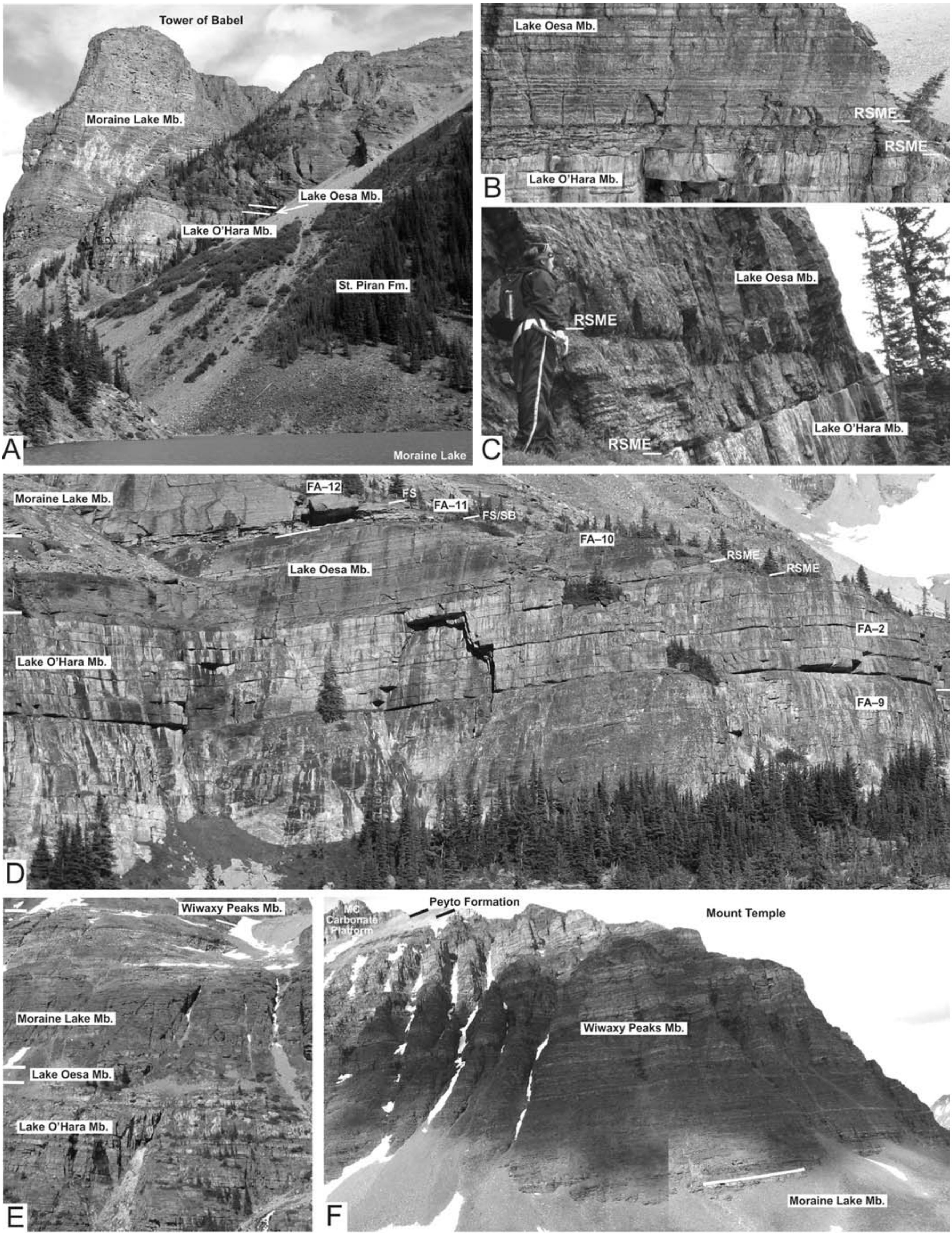
Tower of Babel
Moraine Lake Mb.
Lake Oesa Mb.
Lake O'Hara Mb.
St. Piran Fm.
Moraine Lake
A
Lake Oesa Mb.
RSME
RSME
Lake O'Hara Mb.
B
Lake Oesa Mb.
RSME
Lake O'Hara Mb.
RSME
C
Moraine Lake Mb.
FA–12
FS
FA–11
FS/SB
FA–10
Lake Oesa Mb.
RSME
RSME
FA–2
Lake O'Hara Mb.
FA–9
D
Wiwaxy Peaks Mb.
Moraine Lake Mb.
Lake Oesa Mb.
Lake O'Hara Mb.
E
MC Carbonate Platform
Peyto Formation
Mount Temple
Wiwaxy Peaks Mb.
Moraine Lake Mb.
F

Figure 16

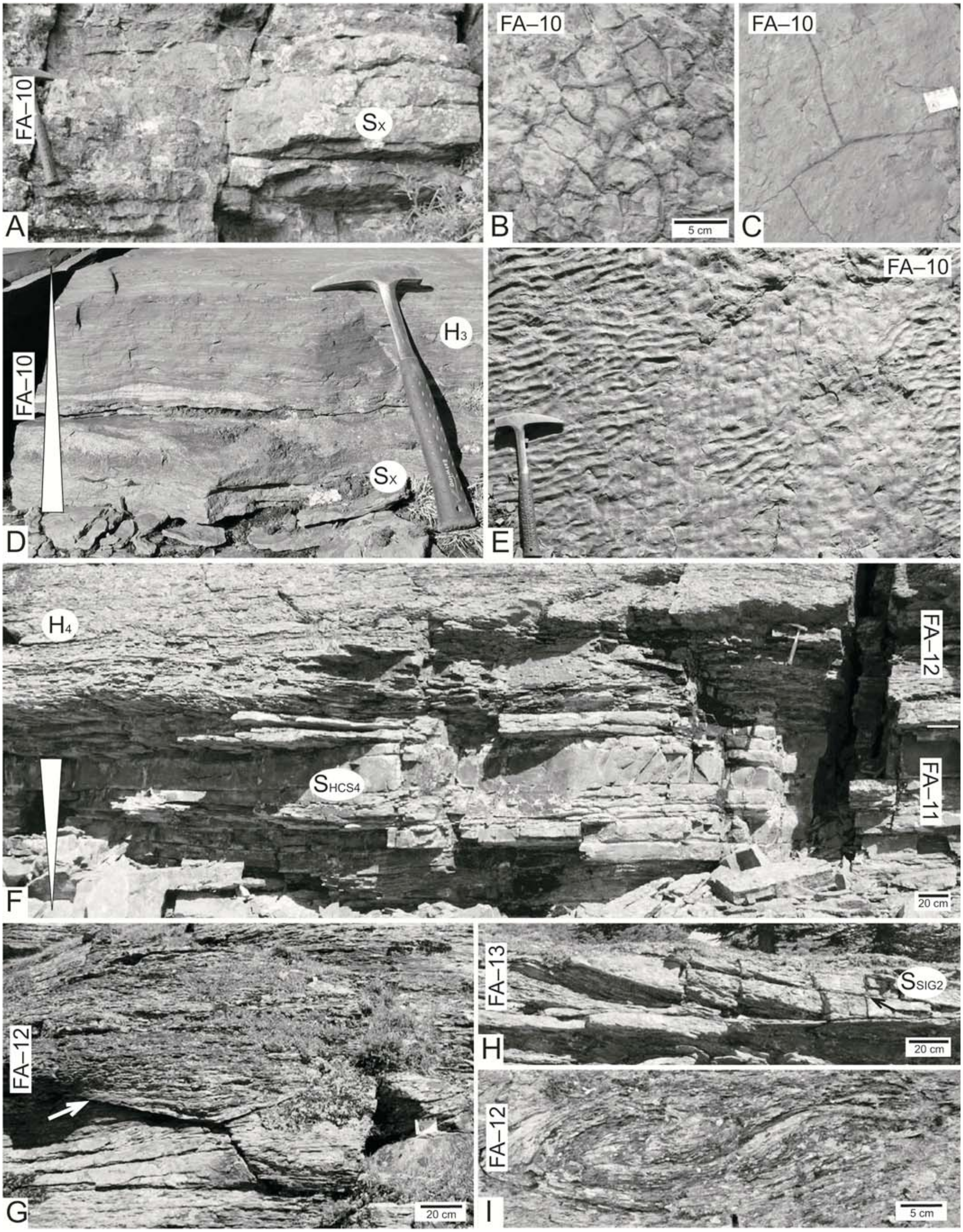
FA–10
Sx
A
FA–10
B
5 cm
FA–10
C
FA–10
H3
Sx
D
FA–10
E
H4
FA–12
FA–11
SHCS4
F
20 cm
FA–12
G
20 cm
FA–13
SSIG2
H
20 cm
FA–12
I
5 cm

Figure 17

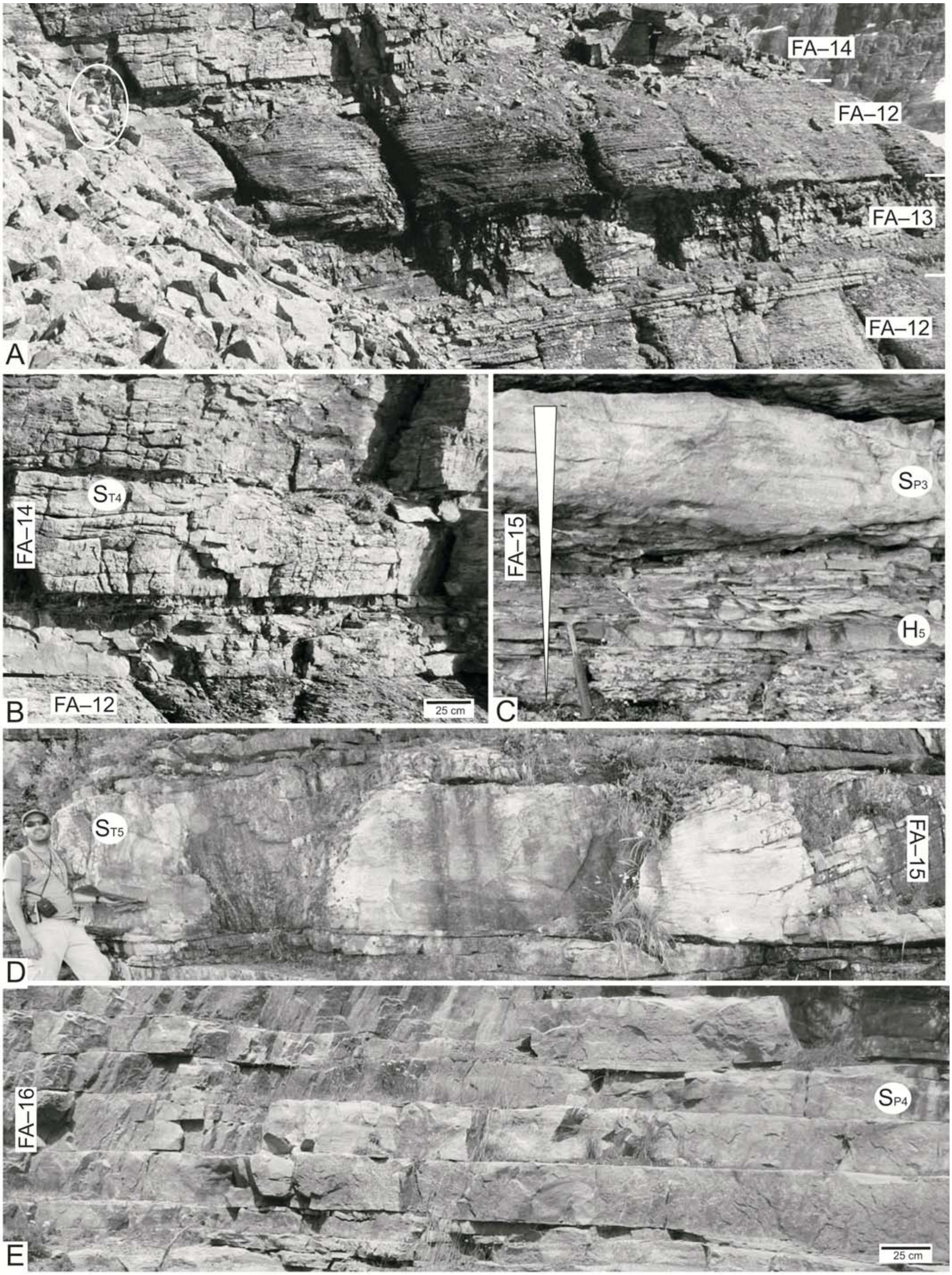
FA–14
FA–12
FA–13
FA–12
A
FA–14
ST4
FA–12
25 cm
B
FA–15
SP3
H5
C
ST5
FA–15
D
FA–16
SP4
25 cm
E

Figure 18

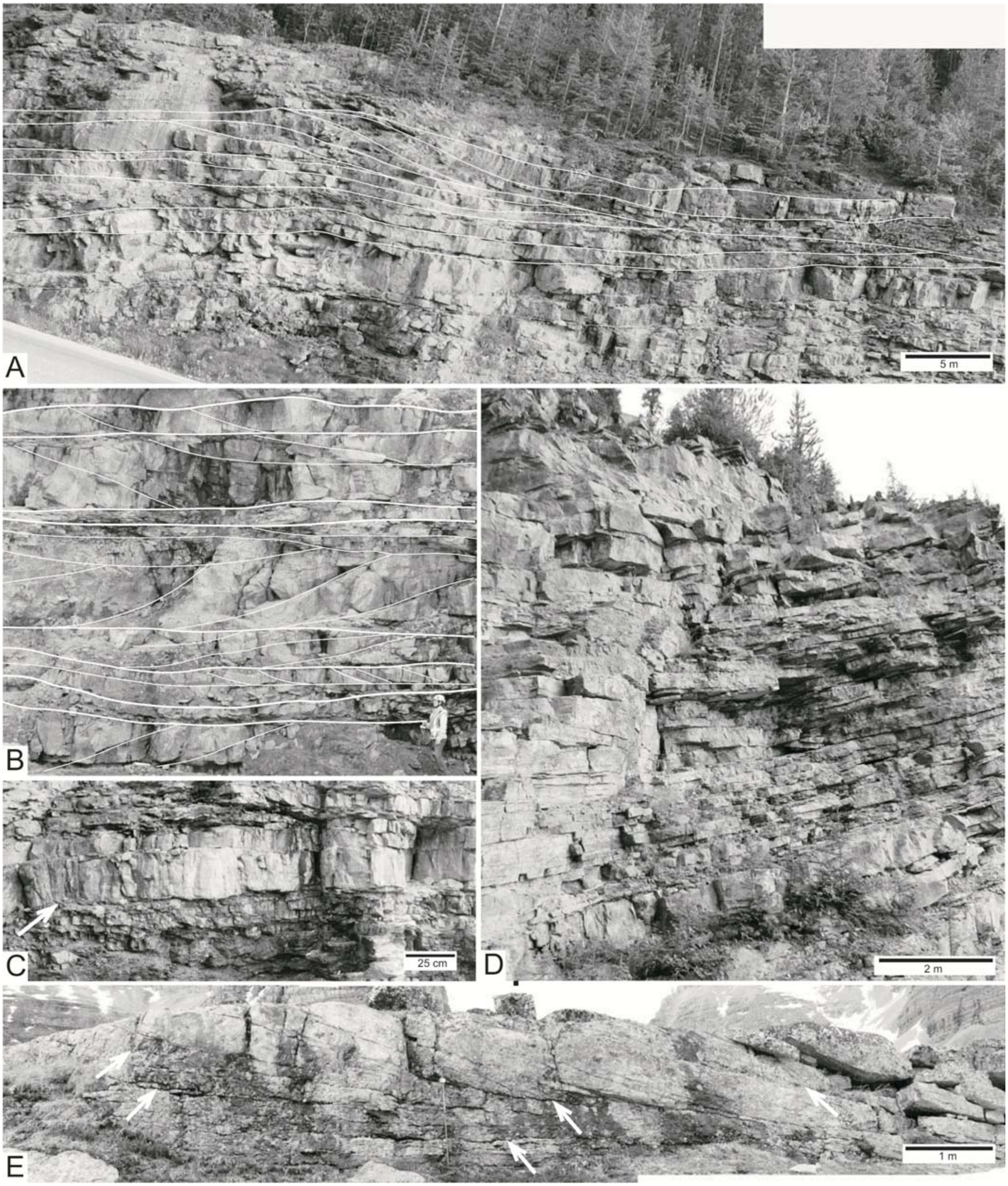

Figure 19

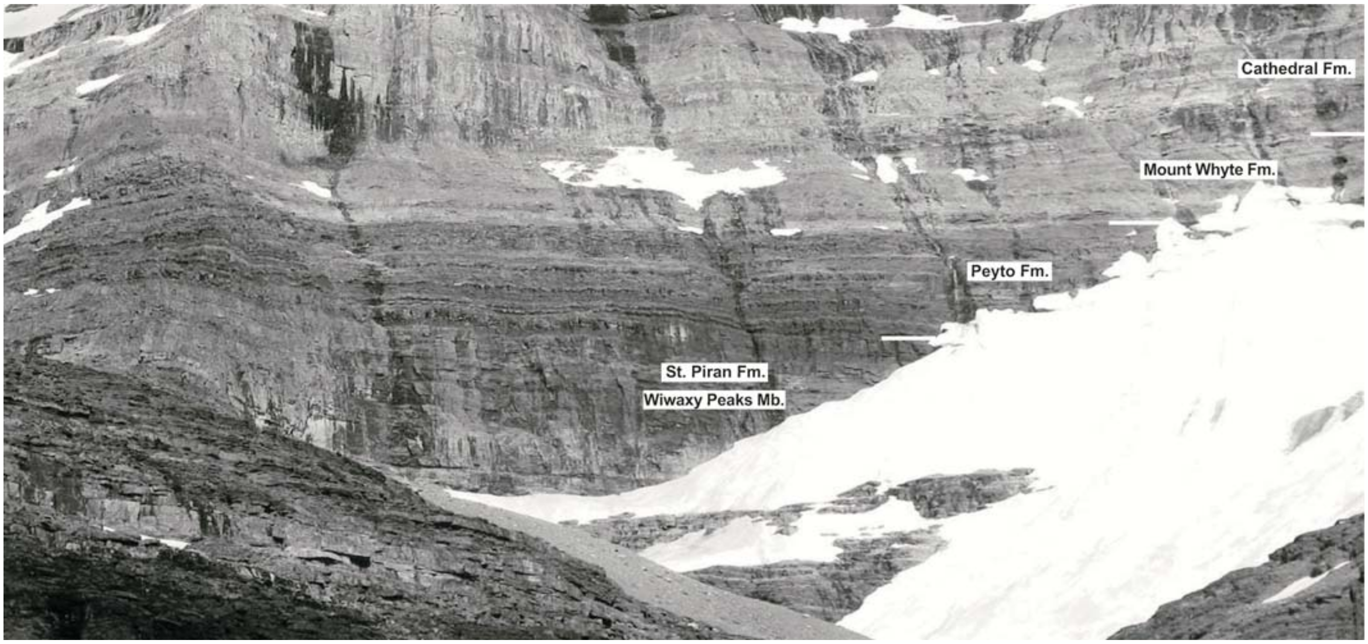
Cathedral Fm.
Mount Whyte Fm.
Peyto Fm.
St. Piran Fm.
Wiwaxy Peaks Mb.

Figure 20

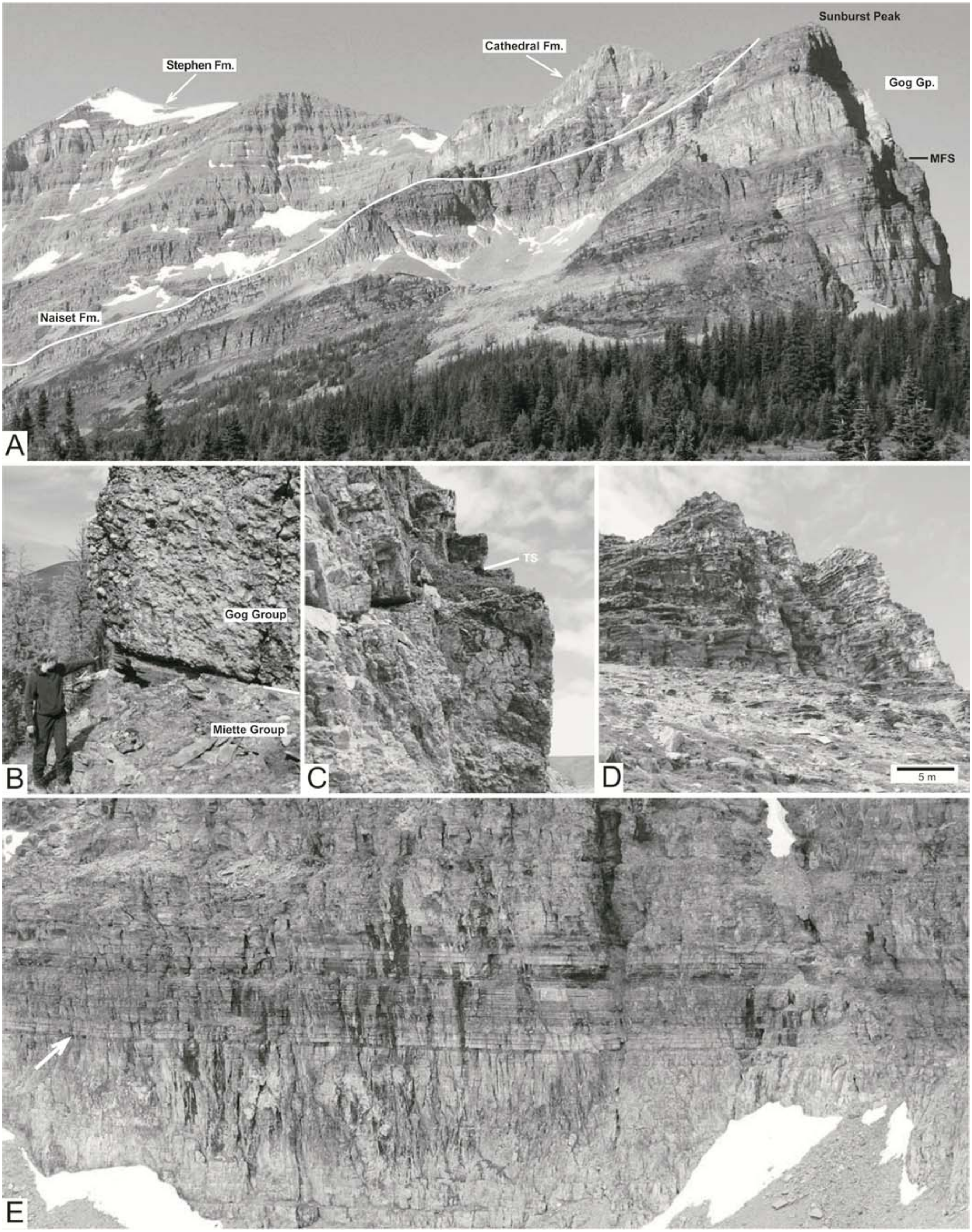
Sunburst Peak
Cathedral Fm.
Stephen Fm.
Gog Gp.
MFS
Naiset Fm.
A
Gog Group
Miette Group
B
TS
C
D
5 m
E

Figure 21

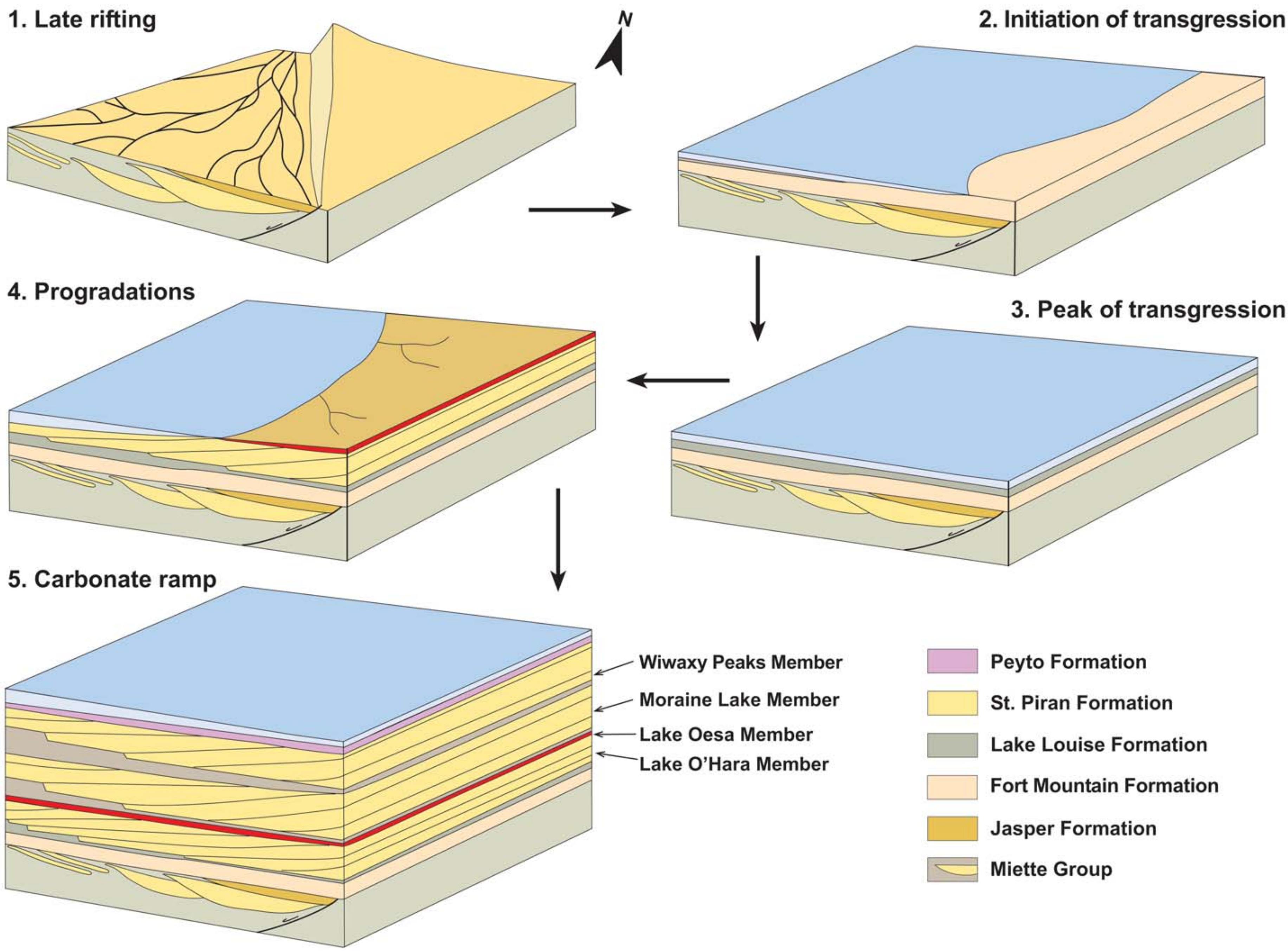
1. Late rifting
N
2. Initiation of transgression
3. Peak of transgression
4. Progradations
5. Carbonate ramp
Wiwaxy Peaks Member
Moraine Lake Member
Lake Oesa Member
Lake O'Hara Member
Peyto Formation
St. Piran Formation
Lake Louise Formation
Fort Mountain Formation
Jasper Formation
Miette Group

Figure 22

CHAPTER 3

A sea-level fall story

Forced-regressive tidal flats: Response to falling sea level in tide-dominated settings

ABSTRACT

During forced regression the coastline advances irrespective of sediment supply, and relocates to a topographically lower position. Forced-regressive deposits are a component of the falling-stage systems tract. They are recognized by a basal unconformity which records erosion during the seaward facies shift, and are in turn capped by another unconformity due to subaerial exposure or wave-ravinement during subsequent transgression. In wave-dominated settings, the basal 'regressive surface of marine erosion' is a scour surface cut by wave action because erosion is needed to maintain the seaward-sloping bathymetric profile in equilibrium with the wave energy. The response in tide-dominated settings has been hitherto unknown. The stratal architecture of the Lower Cambrian Gog Group of the southern Canadian Rocky Mountains reveals a new mechanism for the formation of this surface landward of the lever point of balance between sedimentation and erosion in the subtidal environment. As the shoreline is forced to regress with falling sea level, the laterally continuous tidal flats advance and the preexisting shallow-subtidal compound dunes are scoured by strong tidal currents that carve gradually a new equilibrium profile. We argue that the accretion of intertidal flats on top of subtidal sands is an overlooked yet predictable component of falling-stage systems tracts in tide-dominated settings.

INTRODUCTION

Forced regression is caused by sea-level fall during which coastal sediments prograde irrespective of sediment supply (Catuneanu et al., 2009), in contrast to normal regressions which require a significant sediment flux to maintain a rising shoreline trajectory. This portion of the sea-level curve has historically been assigned to different systems tracts depending on the sequence-stratigraphic model used. On seismic profiles, forced-regressive deposits are characterized by stratal offlap.

The base of a forced-regressive genetic unit is delineated by the ‘basal surface of forced regression’ (Hunt and Tucker, 1992). If this surface truncates underlying strata, recording a seaward facies shift, it is classified as a ‘regressive surface of marine erosion’. This erosion surface is due to scour by wave action seaward of a ‘lever point’ where erosion is needed to maintain the seaward-sloping bathymetric profile that previously was in equilibrium with ambient wave energy. There successive shorefaces are sharp-based, whereas landward of the lever point they have gradational basal contacts (Catuneanu, 2006, p. 124). The top of the forced-regressive unit is delineated by a subaerial unconformity or a wave-ravinement surface.

Forced-regressive deposits have been documented from carbonate and wave-dominated siliciclastic successions (e.g., Plint, 1988; Posamentier et al., 1992; Hunt and Tucker, 1992; Fitzsimmons and Johnson, 2000; Plint and Nummedal, 2000). However, despite sea-level falls having been a common occurrence in the geologic past, only one example of has been described from tide-dominated settings (Olivero et al., 2008). The Lower Cambrian Gog Group in the southern Rocky Mountains of western Canada provides the first example of sharp-based forced-regressive tidal-flat deposits overlying subtidal sandstones.

GEOLOGIC SETTING

During the Early Cambrian, broad shelves developed along many continental margins after the break-up of Rodinia. High accommodation rates driven by thermal subsidence and global sea-level rise (Haq and Schutter, 2008) favored the accumulation of thick successions dominated by cross-stratified shallow-marine sandstones (e.g., Simpson, 1991; Long and Yip, 2009). The Gog Group was deposited on the low-relief and low-gradient continental shelf in West Laurentia. In the area around Lake Louise (Alberta) and Lake O'Hara (British Columbia), the Gog Group unconformably overlies Neoproterozoic deep-water shale and sandstone belonging to the Hector Formation of the upper part of the Miette Group (Fig. 1). This contact represents a major unconformity between Precambrian and Phanerozoic strata, and records the transition from a syn-rift to post-rift tectonic setting. The Gog Group in the study area is formally subdivided into four units, in ascending order, the Fort Mountain, Lake Louise, St. Piran, and Peyto formations (Hein and McMechan, 1994; Appendices 1, 2).

The St. Piran Formation can be broken down into two units separated by a regional unconformity (Figs. 2–4; Desjardins et al., 2010). The lower unit is a progradational succession characterized by subtidal sand sheets (*sensu* Stride et al., 1982). Tidal-flat facies overlie the intervening erosion surface, and are themselves capped by shoreface deposits (Figs. 3–5). The rest of the upper St. Piran Formation comprises two more progradational but purely subtidal intervals.

FACIES

Fifteen facies grouped into four associations are recognized (Appendices 3, 4). The bathymetric framework adopted here for a tide-dominated shelf uses the position of wave-base to separate three main sub-environments: (1) outer shelf (below storm wave base); (2) inner shelf (above storm wave base and below fair-weather wave base); and (3) shallow subtidal (above fair-weather wave base to low-tide line). The wave-dominated zone of this last setting is characterized by hummocky cross-stratified sandstone and comprises the shoreface of common usage.

Subtidal Shelf

The upper part of the lower St. Piran Formation records the growth and migration of a sand-sheet complex in inner-shelf and shallow-subtidal environments during a normal regression. This complex was composed of large to small compound dunes and ripples organized down the sand transport pathway into three main areas: core, front and margin (Desjardins et al., 2010). The core (FA–1) was dominated by medium- to large-sized 2D and 3D compound dunes developed under relatively strong uni-directional currents. The front was characterized by medium-sized and small dunes plus patches of rippled sand and mud deposited in a moderate-energy setting (FA–2). The margin consisted of mud and rippled sand patches (FA−3), and represents the most seaward area off the flank of the complex. Dunes of various sizes comprising the sand-sheet complex gave the shelf topographic relief, in a manner analogous to the dune fields in the North Sea (Stride et al., 1982).

Parasequences that developed at the sand-sheet complex margin and front are characterized by the vertical transition from intercalated very thin- to thin-bedded, very fine- to fine-grained sandstone and mudstone, hummocky cross-stratified, fine-grained sandstone, and highly bioturbated *Skolithos* pipe rock which consists of beds riddled with vertical burrows belonging to *Skolithos linearis*, overlain by planar cross-stratified, fine- to medium-grained sandstone. By contrast, parasequences representing a more proximal position, in the core of the complex, consist of thin- to medium-bedded, planar cross-stratified, fine- to medium-grained sandstone with only scattered *Skolithos* pipe rock. These sandstones are capped by medium- to thick-bedded, cross-stratified sets of planar, trough, and compound cross-stratified, medium- to coarse-grained sandstone, along with hummocky cross-stratified, fine-grained sandstone. However, at the top of the lower St. Piran Formation, an erosion surface truncates a pipe-rock interval, and the expected capping cross-stratified sandstones are absent. This boundary corresponds to the contact between the lower and upper St. Piran Formation.

Tidal Flats

The lowermost part of the upper St. Piran Formation is composed of five fining-upward intervals (parasequences) with sporadic desiccation cracks (FA–4), exhibiting an overall progradational stacking pattern. The package shows uniform thickness in the north–south direction (i.e., along shoreline strike), but an eastward (i.e., landward) thinning, and it is capped by a wave-ravinement surface. Most parasequences are characterized by a sharp base overlain by thin- to medium–bedded, planar, trough and herringbone cross-stratified sandstone containing abundant mud chips and reactivation surfaces. These features are absent in the subtidal sandstones below. They are gradationally followed by intercalated mudstone and wavy- and lenticular-bedded sandstone containing common interference ripples and scattered horizons with desiccation cracks. These facies are typical of sand-flat to mixed- and mud-flat transitions (Klein, 1977).

The lowest parasequence, which sits on the unconformity, is composed only of sand-flat facies that pass westward into a low-energy, bioturbated subtidal sandstone with intercalated mudstone (FA–5). The top of this parasequence is a second erosion surface on which are mud-flat facies. The remaining parasequences exhibit lateral transitions in which more proximal facies become more common to the east. The entire tidal-flat package is capped by hummocky cross-stratified sandstone and planar-laminated sandstone and siltstone (FA–6) which record development of a shoreface.

The erosive contact at the base of the whole tidal-flat package indicates not a gradational transition but an abrupt seaward facies shift. This is because sand-flat deposits erosively overlie subtidal *Skolithos* pipe rock. Absent are intervals of non-bioturbated cross-stratified sandstone that was normally deposited in the shallower, proximal parts of the sand-sheet complex, adjacent to the tidal flats.

DISCUSSION

During sea-level fall, the shoreline advances seaward. This shift is independent of sediment supply. The sea floor is subject to erosion, and the shoreline relocates to a topographically lower point where accretion may or may not take place (Helland-Hansen and Martinsen, 1996). Although the forced-regressive genetic stratigraphic unit has been mainly recognized in wave-dominated successions, falling sea level obviously also affects tide-dominated environments. Modern analogs in mesotidal to macrotidal settings mainly come from Southeast Asia which was affected by Quaternary sea-level fluctuation (e.g., Yang et al., 2001; Ryu et al., 2008).

Along the Jiangsu coastal zone, eastern China, tidal sand-ridges are widely developed in the subtidal zone, whereas tidal flats make up the coastal areas. Sand is delivered mainly by along-shore currents in a macrotidal setting. The coastline prograded during the Holocene simply due to sediment supply, and tidal flats accreted gradationally on top of subtidal sands (Li et al., 2001). Although this case differs from the Gog Group setting, it represents a modern analog but during a normal regression. On the other hand, a closer analogue is the widespread oxidized zone below the unconformity separating Pleistocene and Holocene tidal flats inn Haenam Bay, western Korea, which was due to subaerial exposure during the last glacial maximum (Lim and Park, 2003).

Tidal-flat deposits at the base of the upper St. Piran Formation mantle an erosion surface. A second erosion surface is also present at the base of the second parasequence. Because at both surfaces facies are missing that would have recorded progradation due to gradual shallowing, these surfaces imply an erosional event. No relief that could be related to channel down-cutting was observed. Thus, the jump in facies argues for a forced regression, and these surfaces must have formed in response to sea-level fall, the second being only a minor event.

In sequence stratigraphic parlance both erosional surfaces are classified as a regressive surface of marine erosion (RSME). We propose that these surfaces were formed by two successive processes: (1) as sea level fell, sands previously deposited in the shallow-subtidal zone were affected by strong tidal- and wave-generated currents which planed off the sand sheets; and (2) as the shoreline regressed, strong tidal currents in the lower intertidal zone eroded the upper part of the underlying parasequence consisting of stacked sand sheets until the shoreline reached its new equilibrium profile, producing a regionally diachronous unconformity (Fig. 6). Hummocky cross-stratified sandstones immediately above record a transgressive event followed by shoreface sedimentation. The erosional surface separating it from the underlying tidal-flat package represents an amalgamated sequence boundary and transgressive surface.

CONCLUSIONS

The lowermost interval of the upper St. Piran Formation in the Lower Cambrian Gog Group of western Canada represents the first documented example of a forced-regressive tidal-flat deposit. This provides a new mechanism for the formation of a regressive surface of marine erosion related to tidal scouring, whereby as sea-level falls strong tidal currents erode and remove the upper part of previously deposited subtidal sands. This is recorded by erosionally based tidal–flat facies and a facies jump such that shallow-subtidal deposits are lacking. We place this genetic unit within the falling-stage systems tract.

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Figure Captions

Figure 1. Geologic map of the Bow Valley region of the Rocky Mountains, western Canada, showing the location of the studied outcrops. Pmi = Miette Group; l€gg = Fort Mountain, Lake Louise and lower St. Piran formations; u€gg = upper St. Piran and Peyto formations; €cp = Middle Cambrian platform carbonates; Qd = Quaternary. 1 = Lake Louise; 2 = Lake Agnes; 3 = Lake O'Hara; 4 = Lake Oesa; 5 = Opabin Plateau; 6 = Moraine Lake; 7 = to Redoubt Mountain; 8 = to Bow Peak. BC = British Columbia; AB = Alberta; SK = Saskatchewan

Figure 2. Correlation of measured sections of the uppermost lower and lowermost upper St. Piran Formation oriented parallel to depositional dip. HST = highstand systems tract; FSST = falling-stage systems tract; FS = flooding surface; RSME = regressive surface of marine erosion; WRS = wave-ravinement surface.

Figure 3. Cliff below Lake Oesa showing stratigraphy and interpreted sedimentary environments.

Figure 4. (A–B) Cliff exposure showing RSME between the lower and upper St. Piran Formation and at the base of the second tidal-flat parasequence. (A) Close-up of cliff below Lake Oesa. (B) Lake Agnes.

Figure 5. Correlation of detailed measured sections oriented parallel to depositional dip.

Figure 6. Formation of stratigraphic surfaces during forced regression in a tide-dominated coastal setting. (A) Intertidal-shallow subtidal profile in equilibrium with wave and tidal energy at onset of forced regression. (B) Origin of two regressive surfaces of marine erosion, one in the intertidal area and a second seaward of the lever point. (C) Tidal-flat progradation during stillstand. (D) Wave ravinement causing erosion of the uppermost part of the tidal flat, and formation of a shoreface. (E) Resulting stratal architecture. Vertical scale exaggerated.

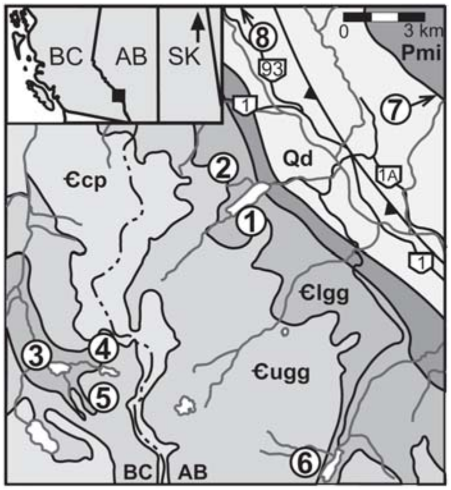
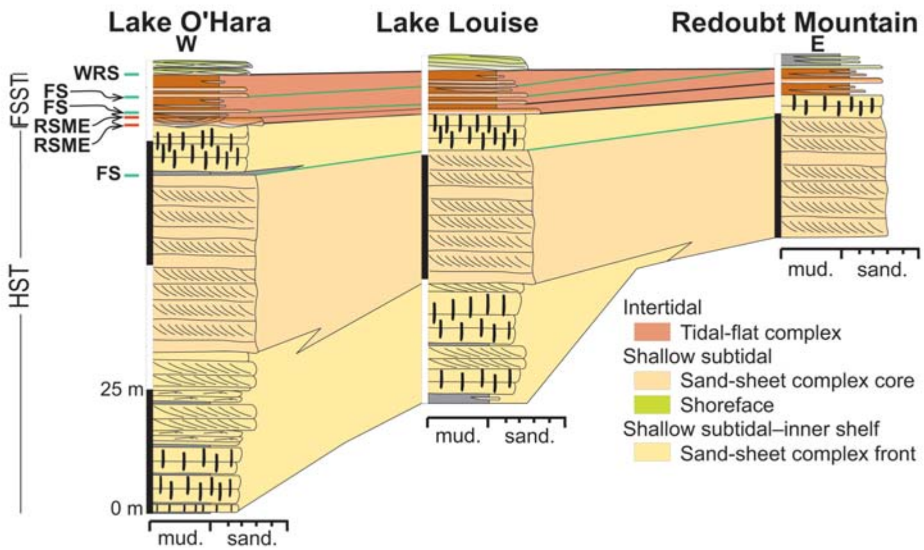


Figure 1



Lake O'Hara
W
Lake Louise
Redoubt Mountain
E
WRS
FS
FS
RSME
RSME
FS
FSST
HST
25 m
0 m
mud.
sand.
mud.
sand.
mud.
sand.
Intertidal
Tidal-flat complex
Shallow subtidal
Sand-sheet complex core
Shoreface
Shallow subtidal–inner shelf
Sand-sheet complex front

Figure 2

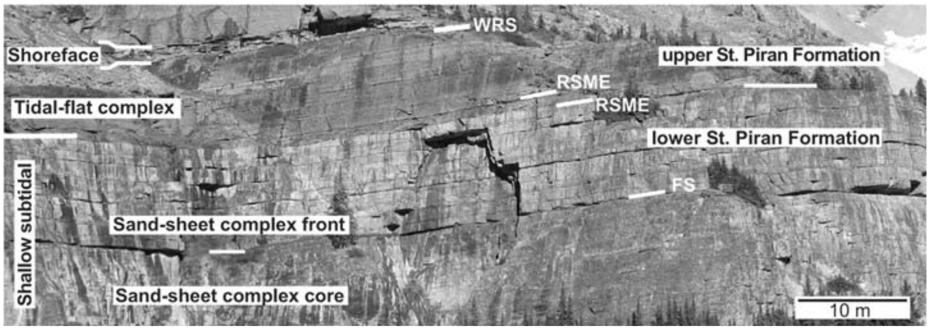

WRS
Shoreface
upper St. Piran Formation
RSME
RSME
Tidal-flat complex
lower St. Piran Formation
FS
Shallow subtidal
Sand-sheet complex front
Sand-sheet complex core
10 m

Figure 3

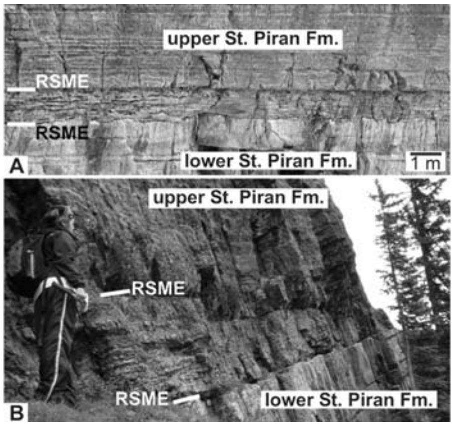

upper St. Piran Fm.
RSME
RSME
A
lower St. Piran Fm.
1 m
upper St. Piran Fm.
RSME
RSME
B
lower St. Piran Fm.

Figure 4

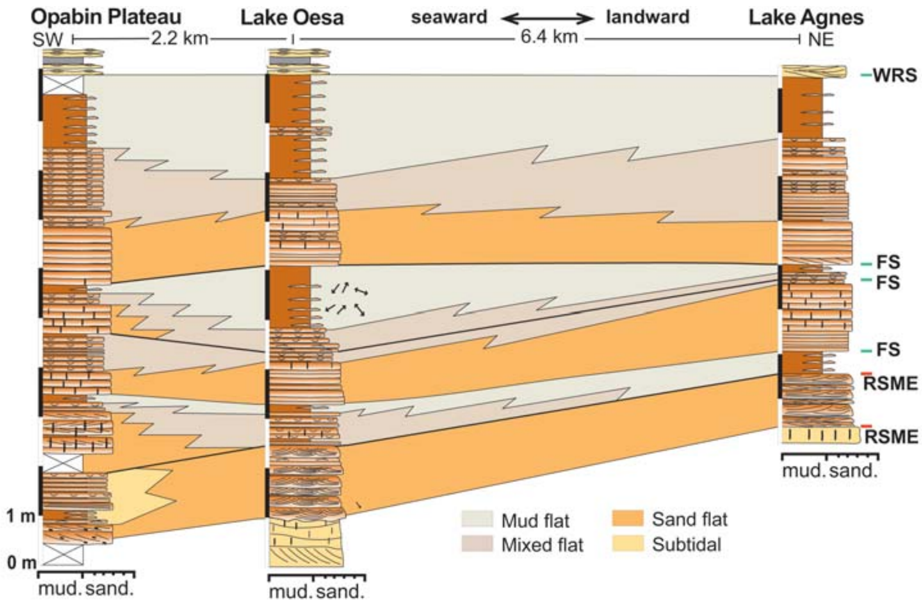

Opabin Plateau
Lake Oesa
seaward
landward
Lake Agnes
SW
2.2 km
6.4 km
NE
WRS
FS
FS
FS
RSME
RSME
1 m
0 m
mud. sand.
mud. sand.
mud. sand.
Mud flat
Mixed flat
Sand flat
Subtidal

Figure 5

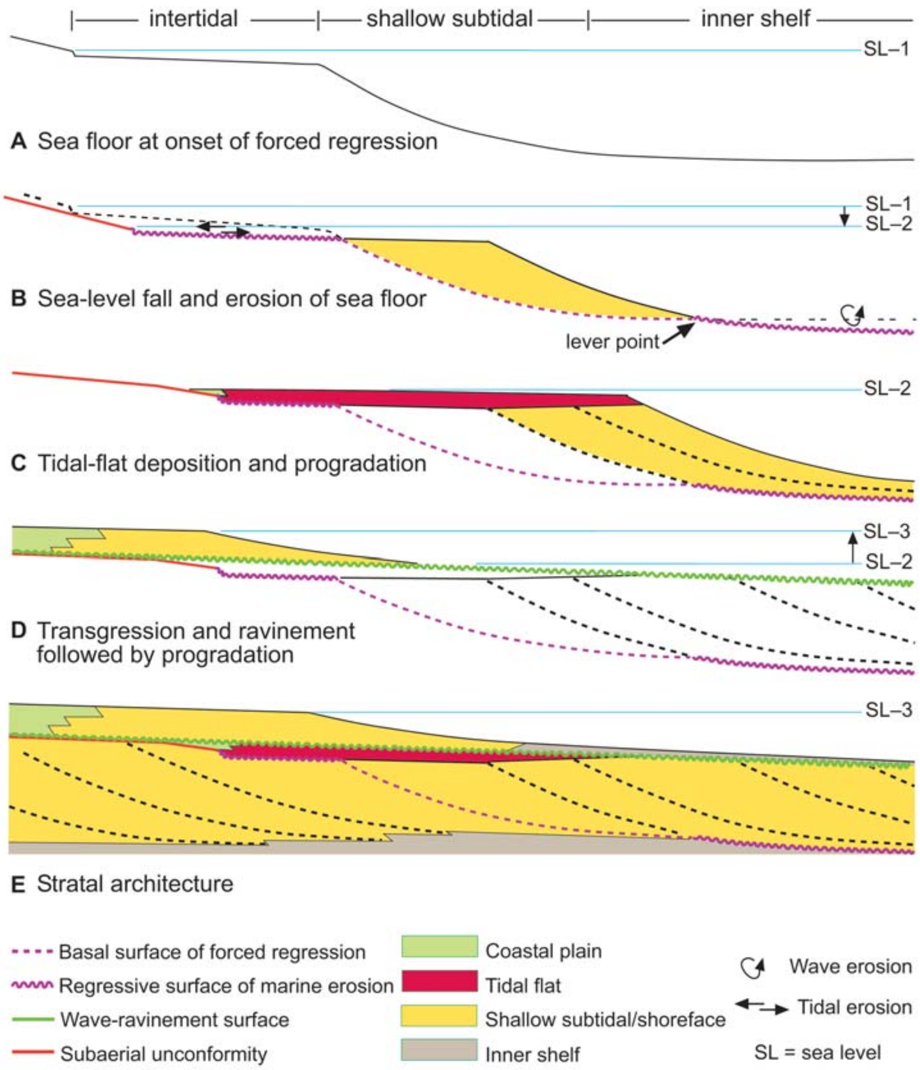
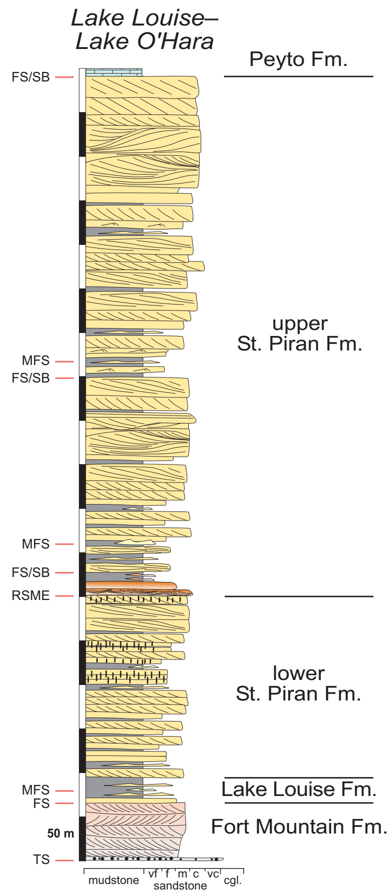
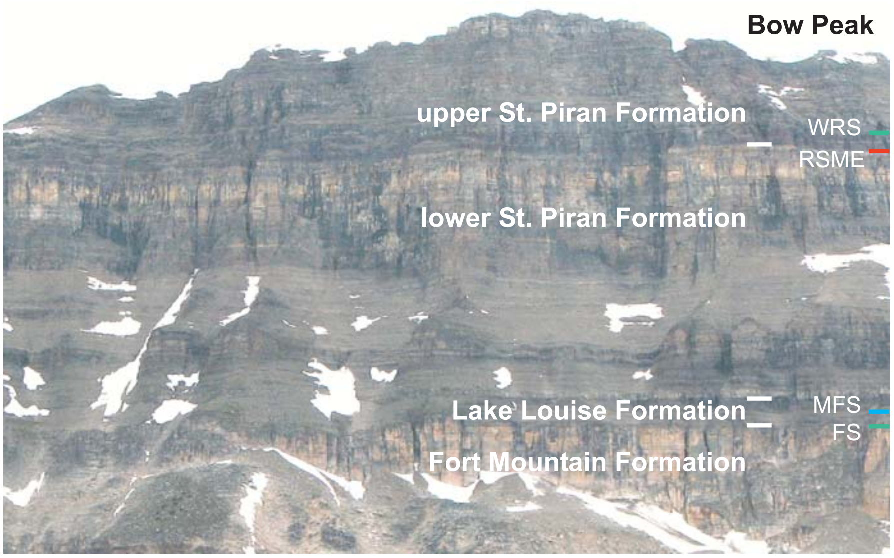

intertidal
shallow subtidal
inner shelf
SL–1
A Sea floor at onset of forced regression
SL–1
SL–2
B Sea-level fall and erosion of sea floor
lever point
SL–2
C Tidal-flat deposition and progradation
SL–3
SL–2
D Transgression and ravinement followed by progradation
SL–3
E Stratal architecture
Basal surface of forced regression
Regressive surface of marine erosion
Wave-ravinement surface
Subaerial unconformity
Coastal plain
Tidal flat
Shallow subtidal/shoreface
Inner shelf
Wave erosion
Tidal erosion
SL = sea level

Figure 6



Composite stratigraphic section of the Gog Group in the Lake Louise and Lake O'Hara sector.

Appendix 1



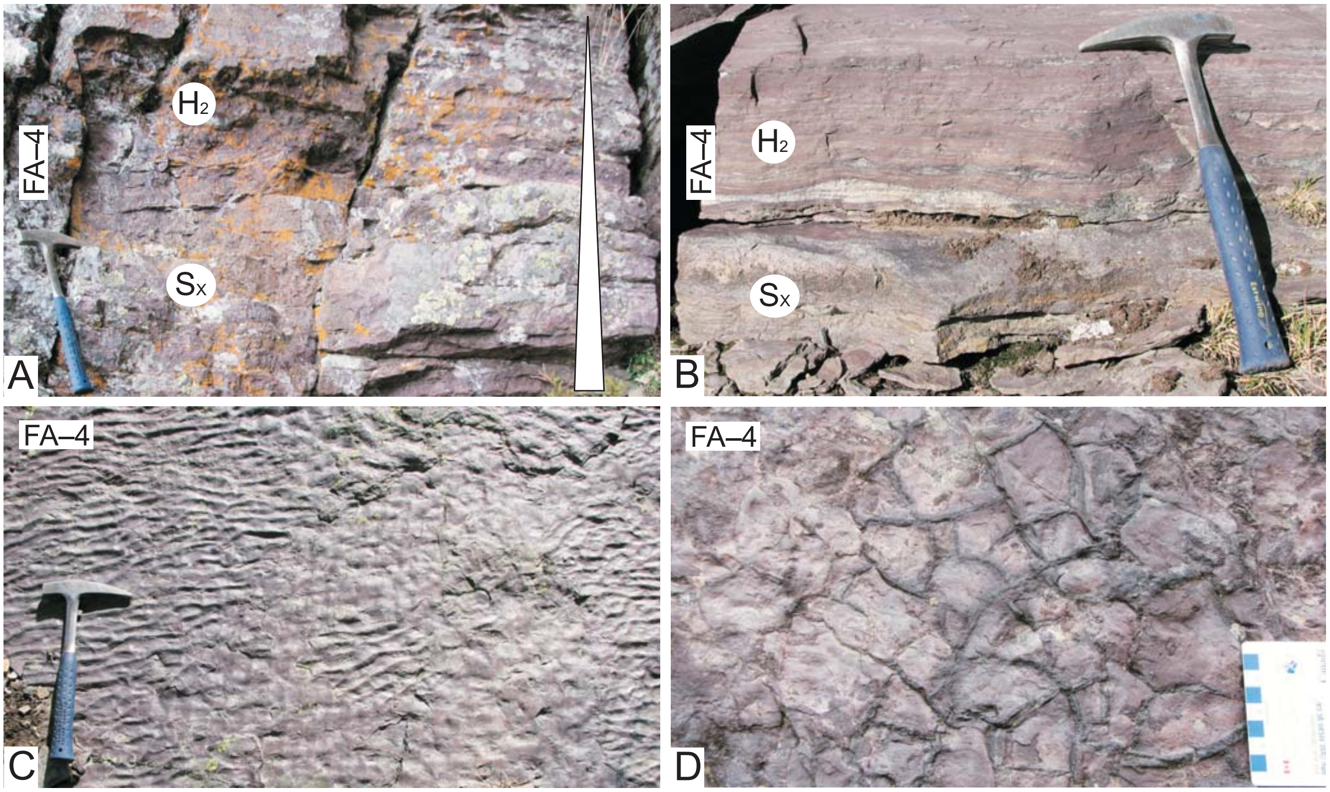
Northeastern flank of Bow Peak showing stratigraphy

Appendix 2

FACIES	LITHOLOGY & SEDIMENTARY STRUCTURES	DEPOSITIONAL PROCESSES	FACIES ASSOCIATIONS	SEDIMENTARY ENVIRONMENTS
S_{P1} Planar cross-stratified sandstone	Thick-bedded, sharp-based tabular bodies, planar and low-angle cross-stratified, very well- to moderately sorted, medium- to very coarse-grained sandstone.	Moderate to high energy; bed-load deposition of large-sized 2D dunes.	FA–1	Shallow subtidal - sand-sheet complex core
S_{T1} Trough cross-stratified sandstone	Thick-bedded, erosionally based, trough cross-stratified, medium- to very coarse-grained sandstone. Local mud drapes and mudstone intraclasts.	Moderate to high energy; bed-load deposition of small- to medium-sized 3D dunes.	FA–1	Shallow subtidal - sand-sheet complex core
S_{P2} Planar cross-stratified sandstone	Medium-bedded, tabular bodies, planar and low-angle cross-stratified, very well-sorted and fine- to medium-grained sandstone. Local mud drapes.	Moderate to high energy; bed-load deposition of medium-sized 2D dunes.	FA–2	Shallow subtidal–inner shelf - sand-sheet complex front
S_{T2} Trough cross-stratified sandstone	Medium- to thick-bedded sets of 10–30 cm thick, trough cross-stratified, very well- to moderately sorted, fine- to medium-grained sandstone.	Moderate to high energy; bed-load deposition as small 3D dunes. Mudstone laminae indicate suspension fall-out during slack-water periods.	FA–2	Shallow subtidal–inner shelf - sand-sheet complex front
Pr *Skolithos* pipe rock	Medium- to very thick-bedded, intensively bioturbated (BI 4–5), very fine- to medium-grained sandstone. Local very thin to thin discontinuous laminae. Vertical trace fossils dominant.	Moderate energy, episodic sand sedimentation. Multiple colonization events by suspension-feeding animals.	FA–2	Shallow subtidal–inner shelf - sand-sheet complex front
S_{HCS1} Hummocky cross-stratified sandstone	Thick-bedded, erosionally based, hummocky and low-angle cross-stratified, very well-sorted, fine- to very fine-grained sandstone. Local internal erosional surfaces and gutter casts.	High energy; bed-load deposition and suspension fall-out due to storm and wave action.	FA–1, 2, 3	Shallow subtidal–inner shelf - sand-sheet complex
H_1 Lenticular-, wavy- and flaser bedded sandstone	Intercalated very thin- to thin-bedded, very fine- to fine-grained sandstone and thinly laminated mudstone. Local planar and ripple cross lamination. 5–30 cm thick heterolithic packages.	Low energy; suspension fall-out and episodic sand deposition. Alternation of current or wave action and slack-water periods.	FA–3	Inner shelf - sand-sheet complex margin
S_X Cross-stratified sandstone	Erosionally to sharp-based, planar and trough cross-stratified, moderately sorted, fine- to medium-grained sandstone. Scattered mudstone intraclasts. Common intercalated ripple cross-laminated sandstone and mud drapes. Scattered *Skolithos linearis*.	Moderate to high energy; bed-load deposition as 3D and 2D dunes. Mudstone laminae indicate suspension fall-out deposition during slack-water periods. Mudstone intraclasts suggest erosion of previously deposited mudstone.	FA–4	Tidal-flat complex
H_2 Lenticular-, wavy- and flaser-bedded sandstone	Very thin- to thin-bedded, very fine- to fine-grained sandstone intercalated with very thin- to medium lamina of mudstone. Common interference ripples, wrinkle marks and desiccation cracks. Scattered shallow-tier horizontal trace fossils.	Low to moderate energy; bed-load deposition of small bedforms (wave and current ripples). Suspension fall-out of fine-grained particles during low-energy periods (i.e. slack water). Mudstone flasers and laminae, and bipolar currents suggest tidal currents.	FA–4	Tidal-flat complex
H_3	Intercalated thin-bedded, very fine- to fine-grained sandstone and mudstone. Local planar and wave-ripple cross lamination. Abundant horizontal and subhorizontal trace fossils.	Low to moderate energy; bed-load deposition of small bedforms. Suspension fall-out of fine-grained particles during low-energy periods.	FA–5	Low-energy shallow subtidal
S_{HCS2} Hummocky cross-stratified sandstone	Erosionally based, thin- to medium-bedded, hummocky and low-angle cross-stratified, very well-sorted, fine-grained sandstone.	High energy; bed-load and suspension fall-out deposition due to storm and wave action.	FA–6	Shoreface

S_L Planar-laminated sandstone	Very thin- to thin-bedded, planar laminated very fine-grained sandstone and siltstone. Locally few very thin to thin lamina of mudstone. Locally *Bergaueria* isp.	Low to moderate energy. Fair-weather suspension fall-out and lower-regime planar-laminated sandstone.	FA–6	Shoreface

Appendix 3: Facies of the lower and upper St. Piran Formation



Tidal-flat facies. (A) Thin- to medium-bedded planar and trough cross-stratified, fine- to coarse-grained sandstone, locally containing mud drapes and chips (S_X), overlain by intercalated very thin- to thin-bedded, ripple cross-laminated. very fine- to fine-grained sandstone and mudstone (H_2) (FA–4). Hammer length is 35 cm. Lake Louise. (B) Fining-upward interval composed of thin-bedded, planar cross-stratified, fine-grained sandstone (S_X) overlain by intercalated very thin- to thin-bedded, ripple cross-laminated, very fine- to fine-grained sandstone and mudstone (H_2). Lake Oesa. (C) Interference ripples in mudstone (H_2). Lake Oesa. (D) Mudstone bedding plane with desiccation cracks. Scale in centimeters Lake Oesa.

Appendix 4

CHAPTER 4

At the dawn of the Phanerozoic…

Skolithos pipe rock and associated ichnofabrics from the southern Rocky Mountains, Canada: colonisation trends and environmental controls in an early Cambrian sand-sheet complex

The Lower Cambrian Gog Group of the southern Rocky Mountains of western Canada offers an opportunity to explore animal–sediment relationships in a high-energy setting, during the early phase of Phanerozoic diversification. Its strata record a sand-sheet complex on the broad pericontinental shelf of West Laurentia. Sedimentological observations allow this complex to be subdivided into three regions: core, front and margin. Six ichnofabrics are recognised.

Skolithos IF–1 is characterised by *Skolithos linearis* in planar cross-stratified sandstone with a bioturbation index of 2 (BI 2). It reflects the episodic colonisation of dune foresets and tops in the complex core and front. *Skolithos* IF–2 consists of *S. linearis* and accessory *Diplocraterion parallelum* in ripple cross-laminated, and planar and trough cross-stratified sandstone (BI 3–4). *Skolithos* IF–3 consists of *S. linearis* and *Planolites montanus* in wavy- and flaser-bedded sandstone (BI 3–5), interfingering with bioturbated mudstone exhibiting *P. montanus* and *Teichichnus rectus*. *Skolithos* IF–2 and 3 indicate persistence of extensive and locally pervasive bioturbation at the front and margin of the complex characterised by moderate hydrodynamic energy and relatively continuous sand sedimentation. *Skolithos* IF–4 is characterised by abundant, relatively large *Skolithos linearis* (BI 3–4) in planar and trough cross-stratified sandstone. *Rosselia* IF–1 consists of *Rosselia* isp. (BI 2–3) in planar cross-stratified sandstone. The occurrence of *Skolithos* IF–4 and *Rosselia* IF–1 in the high-energy facies indicates prolonged periods of dune inactivity and suspended mud in the core of the complex. *Rosselia* IF–2 consists of scattered small *Rosselia* isp. (BI 1–2) in hummocky sandstone. This ichnofabric reflects colonisation in the complex front and margin after major storms.

The presence of constrasting ichnofabrics within a single Early Cambrian sand-sheet complex illuminates how the colonisation trends of suspension and detritus feeders were controlled by factors specific to the various subenvironments.

Keywords: *Skolithos, Rosselia,* Pipe Rock, Ichnofabric, Gog Group, Lower Cambrian

During the Early Cambrian an abrupt increase in the degree and depth of bioturbation occurred in conjunction with the rapid radiation of metazoans, and led to the first mixground ecosystems (Seilacher & Pflüger 1994; Bottjer et al. 2000). Major components of this ecological revolution include the first appearance of vertical burrows and the development of tiered endobenthic communities (Seilacher 1999; McIlroy & Logan, 1999; Mángano & Buatois 2004).

Cambrian shallow-marine sandstones dominated by vertical burrows have been described from many localities around the globe (Table 1), and recognised as indicators of high-energy nearshore environments. One important distinguishing feature of shallow-marine settings at this time was the extraordinarily large amount of sand on continental shelves by comparison to their younger counterparts (Schumm 1968; Dalrymple et al. 1985; Cant & Hein 1986; McKie 1993; MacNaughton et al. 1997). The virtual absence of land plants before the Silurian favoured development of extensive subaerial dune fields and braided fluvial systems on land (Dalrymple et al. 1985; MacNaughton et al. 1997; Rainbird et al. 1997; Long & Yip 2009). Transgressive episodes contributed to the flux of sediment from the continent to the shelf by the flooding and ravinement of pre-existing sandy coastal deposits (Simpson & Eriksson 1990). The Early Cambrian shelf in West Laurentia may have been one of the sandiest of the Phanerozoic, in which the prevailing ecological conditions of this non-actualistic environmental setting favoured the development of dense assemblages of deep-tier suspension feeders.

The term pipe rock was coined by Peach & Horne (1884) in reference to dense populations of *Skolithos* in the Lower Cambrian Eriboll Formation of Scotland, specifically in the Pipe Rock Member. Hallam & Swett (1966) maintained the term pipe rock in their more modern appreciation of these rocks and it has been used since then to describe moderately to highly bioturbated sandstone containing vertical burrows, deposited in both shallow-marine environments (Droser 1991) and, more rarely, continental settings (e.g. Netto 2007).

The Eriboll Formation is now known to be part of a crustal fragment of East Laurentia (e.g. Cawood et al. 2007). This and correlative Early Cambrian sandstones mantling the margins of Laurentia were deposited during the breakup of Rodinia which was accompanied by global transgression (e.g. Haq & Schutter 2008). All these sandstone units are similar to each other in that they are poorly fossiliferous but characteristically locally rich in pipe rock. One of these is the Gog Group of the southern Canadian Rocky Mountains. Spectacularly exposed, these rocks offer an unparalleled opportunity to determine in detail constituent facies, sedimentary architecture and ichnology, which will provide a better understanding of the ecology and depositional dynamics of Cambrian broad, sandy, transgressive continental shelves.

We focus on the lower part of the St. Piran Formation. The main objectives of this paper are to: (1) provide a brief sedimentological description and analysis; (2) characterise subtle differences in ichnofabrics dominated by vertical burrows; and (3) ascertain the palaeoecological and palaeoenvironmental implications of these ichnofabrics.

Stratigraphy

The Lower Cambrian Gog Group is part of a thick sandstone-dominated succession deposited on the broad pericontinental shelf of the margin of west Laurentia. Its outcrops are widely and almost continuously distributed along the Main Ranges of the Rocky Mountains, from Mount Assiniboine to Pine Pass (Fig. 1A).

The Gog Group unconformably overlies Neoproterozoic deep-water shale and sandstone of the Hector Formation comprising the upper part of the Miette Group. The contact between these two units represents a major unconformity between Precambrian and Phanerozoic strata (Aitken 1969). The Gog Group in the Lake Louise and Lake O'Hara area is formally subdivided into four units, in ascending order: (1) Fort Mountain Formation, (2) Lake Louise Formation, (3) St. Piran Formation, and (4) Peyto Formation (Hein & McMechan 1994). North of the North Saskatchewan River a different stratigraphic division and nomenclature exists (Fritz & Mountjoy 1975), while to the south, in the area of Mount Assiniboine, The Gog remains undivided. This study focuses on the lower interval of the St. Piran Formation in the sector between Mount Assiniboine (British Columbia) to Lake Louise (Alberta) and Lake O'Hara (British Columbia) (Fig. 1A–D).

The sedimentology of the Gog Group has only been studied in a reconnaissance fashion (Hein 1987; Hein et al. 1991; Lickorish & Simony 1995). The basal Fort Mountain Formation is a coarsening-upward succession dominated by non-bioturbated sandstone composed of relatively tabular, cross-stratified sets deposited as tidal sand ridges in an inner-shelf setting (Hein et al. 1991). This unit is gradationally overlain by the Lake Louise Formation, which comprises intercalated, thin- to medium-bedded sandstone and shale, within which a maximum flooding surface is inferred. This unit is outer-shelf in aspect. The contact between the Lake Louise and the St. Piran formations is also gradational. The St. Piran Formation can be informally subdivided into two units which are separated by a newly detected unconformity. This surface can be be traced from Mount Assiniboine to Mount Chephren, serving as a datum for regional correlations (Fig. 1D). The lower part of the St. Piran Formation records the migration and overall progradation of a sand-sheet complex in an outer-shelf to inner-shelf environment. Lowstand tidal-flat complexes developed above the erosive surface. These are followed by sand-ridge complexes in an inner-shelf setting (Hein 1987). The limestone and dolomite unit which caps the Gog Group, the Peyto Formation, represents an abrupt shoaling, accompanied by depletion of siliciclastic sediment input (Hein 1987; Aitken 1997).

Facies and facies associations

Six facies and their ichnofabrics (IF) are identified in the lower St. Piran Formation (Table 2). The environmental framework for shelves used by Catuneanu (2006) is adopted herein, whereby the position of the storm wave-base serves to separate two main environments: the inner-shelf above it and the outer-shelf below it. The identification of subaqueous bedforms and the bioturbation intensity or ‘index’ (BI) for each facies follow the terminology of Ashley (1990) and Taylor & Goldring (1993) respectively. The interpretation of these facies is fairly straightforward because of the correspondence to well-understood modern analogues. The facies are grouped into four associations (FAs) (Figs. 2A–D, 3A–B and 5A), which are arranged in a hypothetical proximal–distal position relative to the net sand distribution in the shelf environment.

Facies Association 1–Inner-shelf compound dunes

This consists of 10–30 cm-thick, low-angle and planar cross-stratified (Sp_1), medium- to coarse-grained sandstone within superimposed sets separated by inclined, slightly erosive surfaces. Locally, these surfaces are concave upwards or sigmoidal (Fig. 5B). Cross-stratified sets are 50–200 cm thick. The thickness of individual cross-stratified beds generally increases upwards. Between different sets ripple cross-laminated (Sr_1) and wavy- and lenticular-bedded sandstones (He) occur commonly. Only rarely do the cross-stratified beds contain sparse *Skolithos linearis* burrows (*Skolithos* IF–1).

This association records the migration of two-dimensional compound dunes in an inner-shelf setting. The different cross-stratified beds separated by the inclined surfaces represent small- and medium-sized dunes which migrated on top of the large bedforms (Allen 1980; Dalrymple 1984; Ashley 1990). Wavy- and lenticular-bedded (He) and ripple cross-laminated sandstone (Sr_1) that occur between these cross-stratified sets represent inter-dune areas.

Facies Association 2–Inner-shelf sand-sheet complex margin

This is mainly characterised by 5–10 cm thick, wavy- and lenticular-bedded sandstone (He), 30–80 cm thick, hummocky cross-stratified sandstone (S_{HCS}), and flaser-bedded sandstone (Sr_2). *Rosselia* isp. burrows (*Rosselia* IF–2) occur in the S_{HCS} facies, and *Planolites montanus* and *Teichichnus rectus* are present in the heterolithic intervals.

This association is interpreted as having formed in the margins of a sand-sheet complex, characterised by mud and rippled-sand patches. A position above storm wave-base is inferred for this facies association based on the presence of hummocky cross-stratified sandstone.

Facies Association 3–Inner-shelf sand-sheet complex front

This assemblage comprises thin intervals (3–5 cm) of intercalated wavy- and lenticular-bedded (He), flaser-bedded (Sr_2), ripple cross-laminated (Sr_1), and thin- to medium-bedded trough (St_1) and planar (Sp_1) cross-stratified sandstone, in 80–300 cm thick packages. Hummocky cross-stratified sandstone is also present. Dense assemblages of *Skolithos linearis* and *Diplocraterion parallelum* occur in the sand-dominated facies (*Skolithos* IF–2 and 3), while *Planolites montanus*, *Teichichnus rectus* and *Rusophycus* isp. are present in wavy- and lenticular-bedded sandstone (He).

This association records a more proximal position in the sand-sheet complex than FA–2 with respect to the sediment-dispersal path. This subenvironment was characterised by the presence of medium and small dunes, rippled sand, and mud patches in a moderate-energy environment.

Facies Association 4–Inner-shelf sand-sheet complex core

This consists of amalgamated cross-stratified sets composed of 30–80 cm thick, planar and trough cross-stratified sandstone (St_2, Sp_2) (Fig. 5C). Locally, 3–5 cm thick intervals of wavy- and lenticular-bedded sandstone (He) occur intercalated between the sandstone sets. This association is continuous over almost 30 m in Lake O'Hara and 20 m in Lake Louise (Fig. 1D). The bioturbation pattern varies in this association in that the lower part is mainly non-bioturbated, whereas the uppermost part contains abundant large *Skolithos linearis* and *Rosselia* isp. burrows (*Skolithos* IF–4 and *Rosselia* IF–1).

This association records the migration of medium to large two-dimensional and three-dimensional compound dunes under strong unidirectional currents. Under these high-energy conditions, fine-grained particles were kept in suspension leading to a virtual absence of mudstone in this facies association.

Depositional model

Modern sand-dominated continental shelves, like the North Sea, are characterised by the presence of sand sheets. These extensive features show a tripartite subdivision which includes: (1) a zone of large compound dunes; (2) a zone of small compound dunes, and (3) a zone of sand ripples (Stride et al. 1982). However, limitations exist applying this model to the rock record because vertical successions typically record multiple sand-sheet progradational and retrogradational events. Although these three co-existing sand-sheet subenvironments represent a snapshot view, the model serves as a reasonable template for the facies associations in the lower St. Piran Formation.

The lower part of the formation records an overall progradation phase (Fig. 5A) from a maximum flooding surface located within the Lake Louise Formation (Fig. 1D). The continental shelf was dominated by uni-directitional current-generated bedforms. In contrast to sand sheets of the North Sea, which are being deposited under an accommodation-dominated regime (Stride et al. 1982), the sand-sheet deposits here were deposited under a supply-dominated regime, probably controlled by high rates of sediment supply during relatively uniform subsidence. Distributary-channel deposits of river deltas are inferred to have been present to the east (Lickorish & Simony 1995). Sediment brought to the shelf by rivers was reworked, redistributed and redeposited as sand sheets by the interaction of tidal, longshore and wind-driven currents, and offshore storm surges.

Three different subenvironments are distinguished in the sand-sheet complex and they dictate the occurrence of pipe rock. The most proximal zone, the core of the complex, includes medium to large compound dunes (FA–4), and represents a high-energy subenvironment in terms of current speed gradients. These deposits are the coarsest grained of the succession, and may have been nearest to the coastline. Further seaward along the sand-transport path the subenvironment at the front of the complex is characterised by small- to medium-sized compound dunes, with small dunes and ripples (FA–3). Coarsening- and thickening-upward intervals composed of amalgamated sets suggest the presence of large architectural elements such as bars. The subenvironment at the margins of the complex, that is, immediately seaward of their fronts, comprises rippled-sandstone and mudstone small patches (FA–2). Storm deposits (S_{HCS}) have a greater preservation potential in this most distal subenvironment because the likelihood of erosion decreases down the sediment transport path (Johnson & Baldwin 1996).

Pipe-Rock ichnofabrics

Concepts and methods

An ichnofabric is the internal structure that is developed because of bioturbation or bioerosion (Ekdale & Bromley 1983). Different aspects of the products of an endobenthic community are incorporated, such as degree of bioturbation, tiering and the recognition of different ichnoguilds (Taylor et al. 2003; McIlroy 2004; Mángano & Buatois 2004).

Taylor & Goldring (1993) proposed seven bioturbation indices (BI), in which each grade is based on burrow density, amount of burrow overlap, and proportion of relict original sedimentary fabric. A sedimentary fabric characterised by no bioturbation (0%) corresponds to a BI=0. An ichnofabric that shows sparse bioturbation with few discrete traces corresponds to a BI=1 (1–4 %). Low bioturbation in sediment that still has preserved sedimentary structures corresponds to BI=2 (5–30 %). A BI=3 (31–60 %) describes an ichnofabric with discrete trace fossils, moderate bioturbation and still distinguishable bedding boundaries. BI=4 (61–90 %) is characterised by intense bioturbation, high trace-fossil density, and common overlap of trace fossils, and primary sedimentary structures are mostly erased. A sediment with completely disturbed bedding and showing intense bioturbation corresponds to a BI=5 (91–99 %). Completely bioturbated and reworked sediment, related to repeated overprinting of trace fossils, corresponds to BI=6 (100%). In general, the highest grades, BI=5 and BI=6, have not been observed in the lower St. Piran Formation.

The percentage of bioturbation on bedding planes can also be estimated in the field, using the bedding-plane bioturbation indices (BP-BI) proposed by Miller and Smail (1997): BP-BI 1= 0% ; BP-BI 2=0–10%; BP-BI 3=10–40%; BP-BI 4=40–60%; BP-BI 5=60–100%. These indices were applied only when appropriate bedding planes were found exposed.

Ichnofabric analysis also can help to evaluate the duration and nature of ‘colonisation windows’. Pollard et al. (1993) introduced this concept in order to understand the formation of *Ophiomorpha* ichnofabrics in high-energy settings. They concluded that the time available for colonisation of shifting sands, such as those forming subaqueous dunes, typically occurs only during short periods of quiescence.

Vertical burrows belonging to *Skolithos linearis*, *Rosselia* isp. and *Diplocraterion parallelum* were responsible for creating six ichnofabrics in the lower St. Piran Formation. There has been discussion about the distinction between *Rosselia* and *Monocraterion*. The presence of a concentric lining distinguishes *Rosselia* from *Monocraterion* (Schlirf & Uchman 2005). Jensen (1997) noted that the name *Monocraterion* should only be applied to the holotype of *Monocraterion tentaculum*, which is characterised by a number of tentacle-like structures radiating from the funnel-shaped burrow. In addition, horizontal-burrow ichnofabrics, composed of *Planolites montanus*, *Teichichnus rectus* and *Rusophycus* isp., occurs in wavy- and lenticular-bedded sandstones (He).

Skolithos Ichnofabric 1

This is a mono-ichnospecific assemblage of comparatively narrow vertical burrows assigned to *Skolithos linearis*, with BI=1–2. They are 3–5 mm wide and 21–93 mm long (Fig. 6A–D). *Skolithos* IF–1 occurs in 10–40 cm thick planar cross-stratified, fine- to medium-grained sandstone (Sp_1 and Sp_2) included in FA–1. Colonisation surfaces were located at foresets (Fig. 6A, B) and topsets of these dunes (Fig. 6D).

When current speeds dropped below the threshold of sediment motion, subaqueous dunes became inactive and colonisation windows developed at the foresets (Figure 3A). Also the topsets of these bedforms can be colonised when the dunes became inactive. The low bioturbation index that characterises this ichnofabric most likely reflects single colonisation events related to short-term windows (Fig. 6C, D).

Skolithos Ichnofabric 2

Skolithos IF–2 is dominated by relatively wide *Skolithos linearis* and along with *Diplocraterion parallelum* (Fig. 7A–G). *Skolithos linearis* burrows are 3–12 mm wide and 28–100 mm long. *Diplocraterion parallelum* shafts are 4–6 mm in diameter, and the overall U-shaped burrows are 31–57 mm long and 19–28 mm wide (Fig. 7A, F). This ichnofabric occurs in 20–50 cm thick intervals of flaser-bedded sandstone (Sr_2) (Fig. 7D), trough and planar cross-stratified (St_1 and Sp_1), fine- to medium-grained sandstone (Fig. 7A, C) of FA–3. These packages are typically moderately to highly bioturbated (BI 3–4) (Fig. 7A, C–E, G). Bedding planes are characterised by randomly spaced shafts (Fig. 7B), which only locally cross-cut each other (BP-BI 3–4). Single-event sandstone beds interbedded with wavy- and lenticular-bedded sandstone (He) locally preserve *Rusophycus* isp. burrows at their bases (Fig. 7E). The heterolithic facies (He) contains horizontal burrows attributable to *Planolites montanus* and *Teichichnus rectus*.

The sand-sheet complex front was affected by moderately strong uni-directional currents, inferred from the small size of bedforms (FA–3). Food particles were kept in suspension and promoted the establishment of a dense suspension-feeding ichnofauna. Moderate sedimentation rates, coupled with minor scour erosion, allowed multiple colonisation events of successive generations of *Skolithos linearis* and *Diplocraterion parallelum* producers to occupy the same substrate and develop densely bioturbated beds. Alternation with lower-energy conditions, inferred from the intercalated heterolithic facies (He), allowed the colonisation by a deposit-feeding infauna that produced horizontal burrows.

Skolithos Ichnofabric 3

Skolithos IF–3 consists of trace-fossil assemblages dominated by *Skolithos linearis* and *Planolites montanus* (Fig. 8A–C). *Skolithos linearis* are 5–15 mm wide and 30–125 mm long. This ichnofabric occurs in 30–60 cm thick intervals of wavy-bedded (He) and flaser-bedded (Sr_2) sandstone (Fig. 8A, B). These intervals (Fig. 8C) are typically moderately to highly bioturbated (BI 3–5). *Skolithos* burrows commonly cross-cut mudstone laminae between the sandstones (Fig. 8C).

This ichnofabric reflects multiple colonisation events of deep-tier suspension-feeding and shallow-tier deposit-feeding organisms. The sand-sheet complex front and margin subenvironments were affected by alternating moderate uni-directional currents and slack-water periods, allowing the development of the facies He and Sr_2 (FA–3). Despite the times of periodic calm, a dense suspension-feeding community thrived because there was enough turbulence in general to keep food particles in suspension. Prolonged lower-energy conditions allowed the development of a deposit-feeding infauna characterised by *Planolites montanus*.

Skolithos Ichnofabric 4

This consists of monospecific assemblages of very wide *Skolithos linearis* which are 15–20 mm in diameter and 200–300 mm long. It occurs in 50–100 cm thick, amalgamated, tabular to lenticular, medium- to fine-grained, cross-stratified and massive sandstone beds

(Sp_2, St_2, Sm), with moderate to high bioturbation intensities (BI 3–4) (Fig. 9A, B). Bedding-plane bioturbation intensities corresponds to BP-BI=3–5 (Fig. 9C).

This ichnofabric reflects multiple colonisation events on sand dunes in the core of the sand sheet complex (FA–4), and suggest that the dunes were inactive during colonisation. The *Skolithos* producers fed on suspended particles in agitated waters. The size of the burrows is larger than that of the burrows on the margins (FA–2 and 3), suggesting that the robust organisms were best adapted to cope with environmental conditions of a higher-energy regime. These burrows are remarkably long by comparison with those in *Skolithos* IF–1, 2 and 3, and this suggests that, once established, the organisms were able to retreat into their burrows during turbulence events rather than being washed out.

Rosselia Ichnofabric 1

This ichnofabric consists of monospecific assemblages of *Rosselia* isp. in planar cross-stratified sandstone (Sp_2) (FA–4), having relatively low bioturbation intensities (BI 2–3; BP-BI 3) (Fig. 10A–C). These structures have a funnel shape with a central burrow 8–12 mm wide, surrounded by a concentric lining composed of sand with thin mud laminae (Fig. 10C–I). The diameter of the top of the cone is 21–57 mm. In most specimens analysed here, the concentric laminae are diffuse due to the small quantities of mud and lack of contrast between the burrow sediment infill and the host rock.

The host sedimentary facies (Sp_2) records migration of dunes in a high-energy setting in the complex core. This ichnofabric reflects single colonisation events by the *Rosselia* producers during times of substrate inactivity. As inferred from the mud laminae present in their concentric lining, the *Rosselia* producers are presumed to feed on nutrient-rich, fine-grained material deposited during these low-energy periods.

Rosselia Ichnofabric 2

Rosselia IF–2 consists of small *Rosselia* isp. in hummocky cross-stratified sandstone (S_{HCS}) with a BI=1–2 (Fig. 11A). Total diameter of the structures is 13–23 mm, and length is 60–80 mm. Funnel-shaped linings taper centrally to sub-centrally positioned shafts 3–6 mm wide (Fig. 11B–D). On bedding planes, the trace fossils tend to have an aggregated distribution: some areas contain clusters (BP-BI 2), while others are mostly non-bioturbated. Locally, *Rusophycus* isp. is preserved at the bases of sandstone beds.

Rosselia IF–2 reflects opportunistic colonisation of hummocky cross-stratified sands deposited during major storms at the sand-sheet complex front and margin subenvironments (FA–2 and 3), where a simple ichnofabric of patchy, sparse populations of mid-tier detritus feeders and low bioturbation intensities developed. Turbulence released into the water column large amounts of fine-grained material eroded from the complex, and during the waning phase deposition of very fine-grained sediment favoured detritus feeding while suspension-feeding organisms were restricted.

Ichnofabric distribution

The various ichnofabrics are associated with the same facies associations in the different sections (Figs. 2A–D, 3A–B). The Lake O’Hara sections 1 and 2 start at an interval stratigraphically lower than the sections at Lake Louise (Fig. 1D). The Lake O’Hara sections 1 and 2 start with deposits of FA–1 where only *Skolithos* IF–1 is present. These deposits are followed by facies included in FA–2 and FA–3 exhibiting *Skolithos* IF–2 and 3. *Rosselia* IF–2 is only locally present in FA–3 at Lake O'Hara. The top of the Lower St. Piran Formation at Lake O'Hara Section 1 consists mainly of non-bioturbated trough and planar cross-stratified sandstone (St_2 and Sp_2) (FA–4), only locally containing *Rosselia* IF–1 and *Skolithos* IF–4.

At Fairview Mountain, the lower St. Piran Formation is dominated by hummocky cross-stratified sandstone containing *Rosselia* IF–2 interbedded with relatively thin heterolithic intervals (He) (FA–2) and *Skolithos* pipe rock (*Skolithos* IF–3). The Little Beehive section by Lake Louise, 2.5 km to the northwest, in an interval higher stratigraphically, FA–3 is characterised by thick and continuous pipe rock. These pipe rocks consist of *Skolithos* IF–2 and 3 which are intercalated with only a few non-bioturbated intervals. Higher up in the section at both localities, non-bioturbated intervals are dominant, only locally containing *Skolithos* IF–4 at the uppermost part.

At Mount Assiniboine the distribution of the ichnofabrics is similar to the other localities. The vertical succession of facies associations records a uniformly prograding sand-sheet complex. The lower part of the Lake Magog section is characterised by *Skolithos* IF–3 and *Rosselia* IF–2. An upward increase in sand content is accompanied by the development of thick intervals containing *Skolithos* IF–2. As observed in other localities, the top of the progradational succession is characterised by non-bioturbated planar and trough cross-stratified sandstone (Sp_2 and St_2) (FA–4).

Discussion

The Lower Cambrian Gog Group was deposited on a broad and sandy continental shelf. Sand sheets composed of large to small subaqueous dunes migrated over this shelf. Deep-tier infaunal organisms were dominant in the frontal portions of the sand sheets, while shallow-tier detritus feeders were common around the margins (Fig. 12A–B).

Taphonomy played a role in dictating the final aspect of each of these ichnofabrics. Dune migration scoured the sea floor and removed the shallow-tier trace fossils. Also, if the cone of a *Rosselia* was removed by erosion, for example, the remaining shaft would not be assigned to this ichnogenus. However, evidence for this was not observed, suggesting that partial scour did not occur: entire beds were reworked or not at all. Intercalated lower-energy deposits commonly contain horizontal, shallow- and mid-tier trace fossils, such as *Rusophycus* isp., *Planolites montanus* and *Teichichnus rectus*.

The tracemakers

Skolithos ichnofabrics in this sand-sheet complex comprise dominantly deep dwelling burrows of suspension-feeding organisms. *Skolithos linearis* was produced by a long vermiform soft-bodied animal, which dwelled in vertical domiciles and fed on suspended particles of organic matter, like extant lophophorate phoronids and tentacular-crowned polychaetes do (Pemberton and Frey 1984). Long burrows in some beds of FA–4 indicate that the animal was able to retract its feeding apparatus and retreat deep into its burrow during times of turbulence and scour.

Rosselia ichnofabrics also comprise vertical dwelling burrows. However, the tracemaker was probably a detritus feeder that fed on organic matter attached to fine-grained sediments particles. This is inferred from the presence of mudstone lamina in their concentric linings. The organism may have used some of the mud as a glue to build the wall. Nara (1995) proposed that tenctaculate terebellid polychaetes were the *Rosselia socialis* tracemakers in middle Pleistocene shallow-marine deposits of the Kongochi Formation, Japan. Terebellids, such as the modern *Eupolymnia nebulosa*, live in tubes and use their tentacles to feed preferentially on silt- and mud-sized particles from the adjacent sediment-water interface (Grémare 1988).

Environmental controls and colonisation trends

The relationship between pipe-rock ichnofabric and the sedimentology of the host sandstones have been addressed in a number of previous studies (e.g. Pemberton & Frey 1984; Hiscott et al. 1984; Droser 1991; Droser et al. 1994; Mángano et al. 1996; McIlroy & Garton 2004; Mángano & Buatois 2004). In particular, McIlroy & Garton (2004) and McIlroy (2004) interpreted pipe-rock occurrences as a function of the specific depositional regime, in which sedimentation events were rapid or slow, and continuous or episodic. Slow, continuous sedimentation tended to promote the development of a dense pipe-rock ichnofabric.

The lower St. Piran Formation records temporal and spatial changes of palaeoenvironmental and palaeoecological parameters in an accreting sand-sheet complex. In general, an overall decrease in hydraulic energy and sedimentation rate is inferred from the core to the margin of the complex. Over the sand-sheet complex core and front, food particles were kept in suspension by unidirectional currents and waves, favouring suspension-feeding strategies. However, during times of continuous dune migration, organisms were not able to colonise the shifting substrate. On the other hand, during periods of quiescence after storms in the slightly deeper marginal subenvironment, organic particles fell out and accumulated on the sea floor, favouring colonisation by deposit- and detritus-feeders.

Colonisation trends in modern sand sheets provide partial analogues to better understand this Cambrian example. Benthic shelly faunas and burrow diversity and abundance in subaqueous dunes of the Bristol Channel show a close relationship to the distribution of bottom shear-stress gradients and thus bedform sizes (Wilson 1982, 1986). Areas of large subaqueous dunes contain a sparse fauna, with few species and low faunal densities, comparable to the case of the deposits in FA–1 which only locally contain *Skolithos* IF–1, and to non-bioturbated deposits of the sand-sheet core (FA–4). The stabilisation and deactivation of the complex core allowed intense bioturbation, and the development of *Skolithos* IF–4 and *Rosselia* IF–1. Areas characterised by small subaqueous dunes contain a relatively sparse fauna but exhibit higher diversity than in the area of large subaqueous dunes. This is similar to the development of *Skolithos* IF–2 as in the sand-sheet complex front subenvironment (FA–3). Rippled sand and mud in the modern settings foster an abundant and diverse fauna, similar to the margins of the St. Piran complex (FA–2) where *Skolithos* IF–3 and *Rosselia* IF–2 occur.

The interplay between depositional and taphonomic processes in the specific subenvironments can be depicted in nine taphonomic pathways (*sensu* Buatois and Mángano 2004) (Fig. 13).

Conclusions

The widespread occurrence of shallow-marine sandstones containing ichnofabrics dominated by vertical burrows seems almost diagnostic of the Early Cambrian (Table 1) and, to a lesser extent, the Middle and Upper Cambrian and Early Ordovician. The tiering and intense bioturbation mostly by suspension-feeders record the establishment of a ‘mixground’ ecology very early in the Phanerozoic (Mángano & Buatois 2004).

Although pipe rocks are well known as a salient aspect of the Lower Cambrian sandstones of Laurentia, their environmental distribution has hitherto not been documented in detail. Our results illuminate how the colonisation trends of suspension and detritus feeders in a high-energy setting are controlled by factors specific to the different subenvironments of a sand-sheet complex of regional extent. The core of the complex is only locally bioturbated (*Skolithos* IF–1 and *Rosselia* IF–1) during periodic colonisation windows in shifting subaqueous dunes. The presence of *Skolithos* IF-4 towards the top of FA–4 suggests the deactivation of the complex.

The sand-sheet complex front subenvironment is characterised by highly bioturbated sandstone facies where *Skolithos* IF–2 is extensively developed. The complex margin subenvironment is characterised by lenticular-, wavy- and flaser-bedded sandstone locally containing *Skolithos* IF–3 interfingered with bioturbated mudstone and hummocky cross-statified tempestites colonised by *Rosselia* producers (*Rosselia* IF–2).

The principal limiting palaeoecological factors in this Early Cambrian sand-sheet complex were: (1) food source, which was mainly controlled by the diminishing energy gradient from the sand-sheet complex core to margin subenvironments; and (2) dune dynamics, which were dictated by periodic energy fluctuations. The moderate hydrodynamic energy conditions in the sand-sheet complex front subenvironment favoured the development of pipe-rock ichnofabrics.

There is a dramatic decrease in pipe-rock occurrences after the Ordovician (Droser, 1991). Radiations of predators may have contributed to a decline in large sessile suspension-feeders (McIlroy & Garton 2004). The diversification of marine metazoans during the Ordovician led to greater spatial competition for the infaunal ecospace previously dominated by the *Skolithos* tracemakers.

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Figure captions

Figure 1: Study area and stratigraphy. (A) Map of southwestern Canada showing the location of the studied outcrops in the southern Rocky Mountains: Lake Louise (Alberta), and Mount Assiniboine and Lake O'Hara (British Columbia). Asterisk (*) denotes location of Pine Pass. (B) Northwestern side of Fairview Mountain by Lake Louise. (C) Generalised stratigraphy of the Gog Group at Lake O'Hara. (D) Stratigraphic sections of the lower part of the Gog Group correlated between Mount Assiniboine, Lake O'Hara and Lake Louise. RSME=regressive surface of marine erosion; MFS=maximum flooding surface; TS=transgressive surface; LM=Lake Magog section (50°54'04"N 116°40'40"W); LO1=Lake O'Hara 1 (51°20'27"N 116°19'48"W); LO2=Lake O'Hara 2 (51°21'33"N 116°18'55"W); LO3=Lake O'Hara 3 (51°20'45"N 116°19'48"W);

LB=Little Beehive (51°25’15”N 116°14’14”W); FM= Fairview Mountain (51°23’50”N 116°12’52”W). Legend as in Figure 2.

Figure 2: Measured sections at Lake O’Hara and Lake Louise showing distribution of facies associations and ichnofabrics. (A) Lake O’Hara 2. (B) Lake O’Hara 3. (C) Lake O’Hara 1. (D) Little Beehive.

Figure 3: Detailed measured sections. (A) Lake Magog. (B) Fairview Mountain.

Figure 4: Facies of the lower St. Piran Formation. (A) Lenticular-bedded sandstone (He) (FA–2). *Pl=Planolites montanus*. Fairview Mountain. (B) Bioturbated wavy-bedded sandstone (He) (FA–3). *Te=Teichichnus rectus*; *Pl=Planolites montanus.* Lake O’Hara 2. (C) Intercalated ripple cross-laminated sandstone and mudstone lamina (Sr_1), overlain by thin-bedded trough cross-stratified sandstone (St_1) (FA–3). Lake O’Hara 2. (D) Wavy-bedded sandstone (He) overlain by thin-bedded planar cross-stratified sandstone (Sp_1) (FA–3). Fairview Mountain. (E) Thick-bedded trough cross-stratified sandstone (St_2) (FA–4). Arrows point to reactivation surfaces commonly delineated by mud drapes. Little Beehive. (F) Thick-bedded planar cross-stratified sandstone (Sp_2) intercalated with ripple cross-laminated sandstone (Sr_1) (FA–1). Lake O’Hara 2. (G) Medium-bedded planar cross-stratified sandstone (Sp_1) (FA–3). Arrows point to mud drapes in the foresets. Lake O’Hara 2. (H) Hummocky cross-stratified sandstone (S_{HCS}) (FA–3). Near Lake O’Hara 2.

Figure 5: Facies associations of the lower St. Piran Formation. (A) Distribution of the different facies associations in the lower St. Piran Formation at Lake O’Hara. Trees≈10 m. (B) Inner-shelf thick-bedded compound dune deposits (FA–1) showing the sigmoidal-shaped surfaces (arrows) separating different cross-stratified beds. Rock hammer=35 cm.

Lake O'Hara 1. (C) Inner-shelf very thick-bedded compound dune deposits (FA–4). Lake O'Hara 3. Person≈1.75 m.

Figure 6: *Skolithos* ichnofabric 1. *Sk*=*Skolithos linearis*. (A) *Skolithos linearis* extending down from the upper surfaces of the foresets of medium-bedded, planar cross-stratified sandstone (Sp_1) (FA–1). Lake Magog. (B) Sketch showing positions of erosion and colonisation surfaces (CS). (C) Medium-bedded trough cross-stratified sandstone (St_1) (FA–1) showing sparse *S. linearis*. Lake Magog. (D) *Skolithos linearis* extending down from the upper surface a planar cross-stratified sandstone (Sp_1) (FA–1). Lake O'Hara 1.

Figure 7: *Skolithos* ichnofabric 2. *Sk*=*Skolithos linearis*; *Dp*=*Diplocraterion parallelum.* (A) Abundant *S. linearis* (BI 4) in medium-bedded planar cross-stratified sandstone (Sp_1) (FA–3), containing several erosion surfaces (white arrows). Fairview Mountain. (B) Bedding plane view of *S. linearis* (FA–3). Fairview Mountain. (C) *Skolithos linearis* crossing bedding contacts. Fairview Mountain. (D) Dense *S. linearis* assemblage (BI 5) (FA–3). Little Beehive. (E) Ripple cross-laminated sandstone (Sr_2) containing abundant *S. linearis* (BI 3) intercalated with wavy- and lenticular-bedded sandstone (He) (FA–3). Lake Magog. (F) Bedding-plane view of *S. linearis* and *D. parallelum* (FA–3). Little Beehive. (G) Parasequence recording a progradational cycle of the sand-sheet complex front (FA–3), showing the vertical transition from wavy-bedded and rippled cross-laminated sandstone to highly bioturbated sandstone (BI 5), which are caped by non-bioturbated parallel-laminated sandstone. Lake O'Hara 1.

Figure 8: *Skolithos* ichnofabric 3. *Sk*=*Skolithos linearis*. (A) Highly bioturbated (BI 5) wavy-bedded sandstone (He) and flaser-bedded sandstone (Sr_2) (FA–2). Lake Magog. (B) Highly bioturbated (BI 4) flaser-bedded sandstone (Sr_2) (FA–3). *Skolithos linearis* cross-

cutting several sandstone and mudstone lamina sets. Lake Magog. (C) Highly bioturbated interval containing *S. linearis* and *Planolites montanus* (*Skolithos* IF-3), overlying medium-bedded planar cross-stratified sandstone (Sp_1) and lenticular- and wavy-bedded sandstone (He) (FA–3). Lake O'Hara 2.

Figure 9: *Skolithos* ichnofabric 4. *Sk*=*Skolithos linearis*. (A) Tabular to lenticular, medium- to thick-bedded cross-stratified sandstone (Sp_2 and St_2) (FA–4) containing robust *S. linearis*. Lake O'Hara 3. (B) Massive sandstone (Sm) containing relatively larger *S. linearis* compared to those comprising *Skolithos* IF–1, 2 and 3. Lake O'Hara 3. Rock hammer=35cm. (C) Bedding plane view of *S. linearis*. Lake O'Hara 3.

Figure 10: *Rosselia* ichnofabric 1. *Ro*=*Rosselia* isp. (A) Bedding-plane view of massive sandstone (Sm) (FA–4) with pits corresponding to weathered transverse cross-sections of *Rosselia* isp. Lake O'Hara 3. (B) Close-up view of A with transverse cross-sections of *Rosselia* isp. showing concentric lining. Lake O'Hara 3. (C) Two side-by-side *Rosselia* isp. transverse cross-sections showing alternating concentric sandstone and mudstone laminae. Lake O'Hara 3. (D) Cut surface on one side of *Rosselia* isp. showing mudstone (dark) alternating with sandstone (light) laminae. (E) Sketch of *Rosselia* showing axial tube and funnel-shaped concentric lining. Dotted lines indicate position of polished surfaces shown in F–I. (F) Longitudinal section. (G–I) Three transverse sections of the same burrow 2 cm apart.

Figure 11: *Rosselia* ichnofabric 2. *Ro*=*Rosselia* isp. (A) Hummocky cross-stratified sandstone (S_{HCS}) (FA–2) containing *Rosselia* isp. which extend down from upper surface. Fairview Mountain. (B) Parallel-laminated sandstone bed showing common *Rosselia* isp. Fairview Mountain. (C) Longitudinal cross-section of *Rosselia* isp. showing its funnel

shape. Lake Magog. (D) Transverse cross-sections of *Rosselia* isp. Lake Magog. Coin=2.5 cm.

Figure 12: (A) Depositional model. (B) Environmental distribution and dynamics of the different ichnofabrics in an Early Cambrian sand-sheet complex as exemplified by the lower St. Piran Formation, Gog Group.

Figure 13: Taphonomic pathways in different subenvironments of an Early Cambrian sand-sheet complex. *S.*IF=*Skolithos* ichnofabrics; *R.*IF=*Rosselia* ichnofabrics

Table Captions

Table 1: Selected pipe-rock occurrences. The originally interpreted depositional settings are harmonized following the terminology of Sutter (2006) and Dalrymple (1992). Early Cambrian=542–513 Ma; Middle Cambrian=513–501 Ma; Furongian=501–488.3 Ma (Shergold & Cooper 2004).

Table 2: Facies in the lower St. Piran Formation, Gog Group.

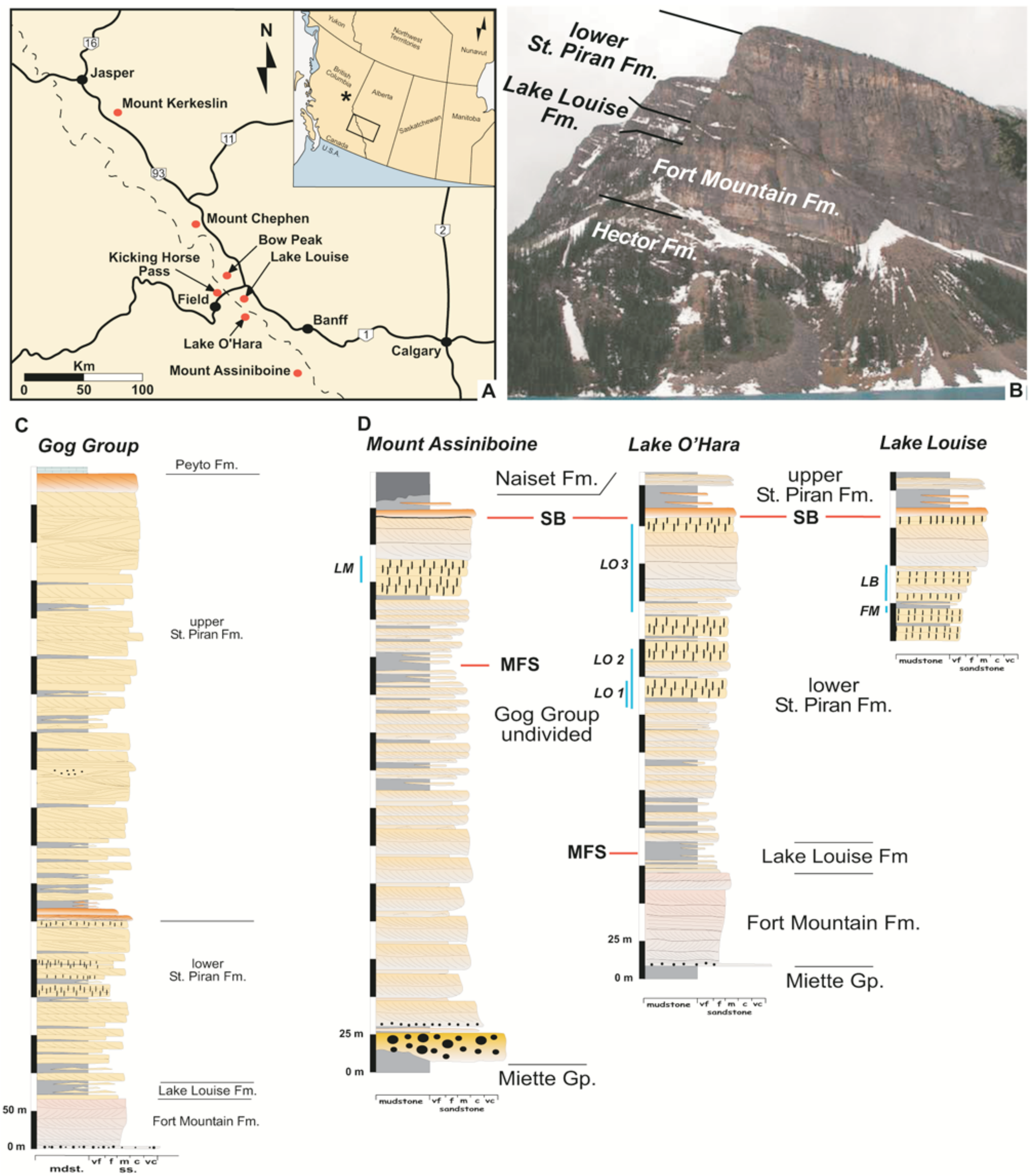
Stratigraphic Unit and Location	**Age**	**Ichnofauna**	**Depositional Environment**	**References**
Eribol Sandstone Fm. (Scotland)	Early Cambrian	*Skolithos linearis*, "*Monocraterion*" isp.	shoreface, shelf	Hallam & Swett (1966) McKie (1990) McIlroy & Garton (2004) Davies et al. (2009)
Hampton. & Erwin fms., Chillowee Gp. (Virginia)	Early Cambrian	*Skolithos linearis*	shoreface, intertidal	Simpson & Erikson (1990)
Antietam Fm., Chillowee Gp. (Virginia)	Early Cambrian	*Skolithos linearis* "*Monocraterion*" isp.	shoreface, intertidal	Simpson (1991)
Hardyston Fm. (Pennsylvania)	Early Cambrian	*Skolithos linearis*	shoreface	Simpson et al. (2002)
Chickies Quartzite (Pennsylvania)	Early Cambrian	*Skolithos linearis* "*Monocraterion*" isp.	intertidal	Goodwin & Anderson (1974)
Zabriskie Quartzite (Death Valley region)	Early Cambrian	*Skolithos linearis*	shoreface, inner shelf	Prave (1991)
Wood Canyon Fm. (Death Valley region)	Early Cambrian	*Skolithos linearis*	shoreface	Droser (1991)
Mt. Simon Fm. (Wisconsin)	Early Cambrian	*Skolithos* isp. *Arenicolites* isp.	intertidal	Driese et al. (1980)

Bradore Fm. (Labrador, Canada)	Early Cambrian	*Skolithos linearis*	estuary mouth, intertidal–subtidal	Hiscott et al. (1984) Pemberton & Frey (1984)
Campanario Fm., Mesón Gp. (northwestern Argentina)	Early–Middle Cambrian	*Skolithos linearis* *Diplocraterion parallelum* *Syringomorpha nilssoni* *Syringomorpha* isp. *Arenicolites* isp.	intertidal–subtidal	Mángano & Buatois (2004)
Riley Fm. (Texas)	Middle Cambrian–Furongian	*Diplocraterion* isp., *Skolithos linearis*	intertidal	Cornish (1986)
Postdam Fm. (Pennsylvania & New York State)	Furongian	"*Monocraterion*" isp. *Skolithos* isp. *Diplocraterion* isp.	intertidal	Bjerstedt & Erickson (1989)
Santa Rosita Fm., Pico de Halcón Member (northwestern Argentina)	Furongian	*Skolithos linearis*	estuary mouth	Mángano et al. (1996)
Bliss Fm. (New Mexico)	Furongian–Tremadocian	*Skolithos* isp.	shoreface	Chafetz et al. (1986)
Cabos Series (northern Spain)	Furongian–Tremadocian	*Skolithos linearis*	intertidal–subtidal, shoreface	Baldwin (1977)

Table 1

FACIES	LITHOLOGY & SEDIMENTARY STRUCTURES	DEPOSITIONAL PROCESSES	TRACE FOSSILS & BIOTURBATION INDEX (BI)	DISTRIBUTION	FIGURE
He **Lenticular- and wavy-bedded sandstone**	1–3 cm thick, very fine- to fine-grained sandstone; interbedded with 0.1–5 cm thick, thinly laminated mudstone. Local planar and ripple cross-lamination. Preserved as 3–30 cm thick heterolithic packages.	Low-energy; suspension fall-out and episodic sand deposition. Type of bedding related to the alternation of current or wave action and slack-water periods.	*Planolites montanus* and *Teichichnus rectus* BI = 0–4	Facies Association 1, 2, 3, 4	4A–B
Sr_1-Sr_2 **Ripple cross-laminated sandstone**	Current-ripple cross-laminated, very well-sorted, very fine- to medium-grained sandstone. **Sr_1**: 10–30 cm thick packages of 2–7 cm thick very fine- to fine-grained sandstone sets, separated by thin mudstone flasers. Laterally and vertically associated to trough cross-stratified sandstone. **Sr_2**: 0.5–2 cm thick, flaser-bedded sandstone. Preserved as 10–100 cm thick packages.	Low- to moderate-energy; bed-load deposition of small bedforms (current ripples). Mudstone flasers and laminae reflect alternation of bed-load deposition and suspension fall-out. Suspension fall-out deposition of fine-grained particles during low-energy periods (i.e. slack water). Mudstone flasers and laminae suggest currents of tidal origin.	**Sr_1**: Bioturbation absent. BI = 0 **Sr_2**: *Skolithos linearis*, *Diplocraterion parallelum*, and *Planolites montanus*. BI = 3–5	**Sr_1**: Facies Association 1, 3 **Sr_2**: Facies Association 2, 3	4C
St_1-St_2 **Trough cross-stratified sandstone**	Trough cross-stratified, very well- to moderately sorted, fine- to very coarse-grained sandstone. **St_1**: 20–60 cm thick sets of 10–30 cm thick, fine- to medium-grained sandstone beds. Locally associated to facies Sr. **St_2**: 30–60 cm thick, erosionally based, trough cross-stratified, medium- to coarse-grained sandstone. Local mud drapes and mudstone intraclasts.	Moderate- to high-energy; bed-load deposition of 3D dunes. St_1 related to small dunes. Mudstone lamina within indicates suspension fall-out deposition during slack-water periods. Mudstone intraclast suggests erosion of previously deposited mudstone. St_2 related to small- to medium-sized 3D dunes.	**St_1**: *Skolithos linearis* and *Diplocraterion parallelum* BI = 0–4 **St_2**: *Skolithos linearis* locally observed. BI = 0–2	**St_1**: Facies Association 3 **St_2**: Facies Association 4	4C, E
Sp_1-Sp_2 **Planar cross-stratified sandstone**	Tabular bodies, planar and low-angle cross-stratified, very well- to moderately sorted, fine- to very coarse-grained sandstone. **Sp_1**: 10–30 cm thick, sharp based tabular beds, very well-sorted and fine- to medium-grained sandstone. Local mud drapes. **Sp_2**: 30–80 cm thick, sharp-based bodies, very well- to moderately sorted, medium- to very coarse-grained sandstone.	Moderate- to high-energy; bed-load deposition of 2D dunes. Sp_1 related to medium-sized dunes. Sp_2 related to small-sized dunes.	**Sp_1**: *Skolithos linearis* BI = 0–4 **Sp_2**: *Rosselia* isp. and *Skolithos linearis* delineate the upper surface of the beds. BI = 0–4	**Sp_1**: Facies Association 1, 3 **Sp_2**: Facies Association 4	4D, G, F
S_{HCS} **Hummocky cross-stratified sandstone**	Erosionally based, 30–80 cm thick, hummocky and low-angle cross-stratified, very well-sorted, fine- to very fine-grained sandstone. Local internal erosional surfaces and gutter casts.	High-energy; Bed-load and suspension fall-out deposition from turbidity currents and high energy waves. Sand eroded from shoals and transported seaward.	*Rosselia* isp. BI = 0–2	Facies Association 2, 3	4H
Sm **Massive sandstone**	Tabular beds, 20–100 cm thick, well sorted, medium- to coarse-grained quartzite; massive in aspect.	Low- to moderate-energy; bed-load deposition under low-flow regime. Massive nature probably related to uniformity in grain size.	*Skolithos linearis* BI = 0–3	Facies Association 3, 4	

Table 2



A
Jasper
Mount Kerkeslin
Mount Chephen
Bow Peak
Lake Louise
Kicking Horse Pass
Field
Banff
Lake O'Hara
Calgary
Mount Assiniboine
Km
0 50 100
N
B
lower St. Piran Fm.
Lake Louise Fm.
Fort Mountain Fm.
Hector Fm.
C
Gog Group
Peyto Fm.
upper St. Piran Fm.
lower St. Piran Fm.
Lake Louise Fm.
Fort Mountain Fm.
50 m
0 m
mdst.
vf f m c vc
ss.
D
Mount Assiniboine
Lake O'Hara
Lake Louise
Naiset Fm.
SB
upper St. Piran Fm.
LM
LO 3
LB
FM
MFS
LO 2
LO 1
Gog Group undivided
lower St. Piran Fm.
Lake Louise Fm
Fort Mountain Fm.
Miette Gp.
25 m
0 m
mudstone
vf f m c vc
sandstone

Figure 1

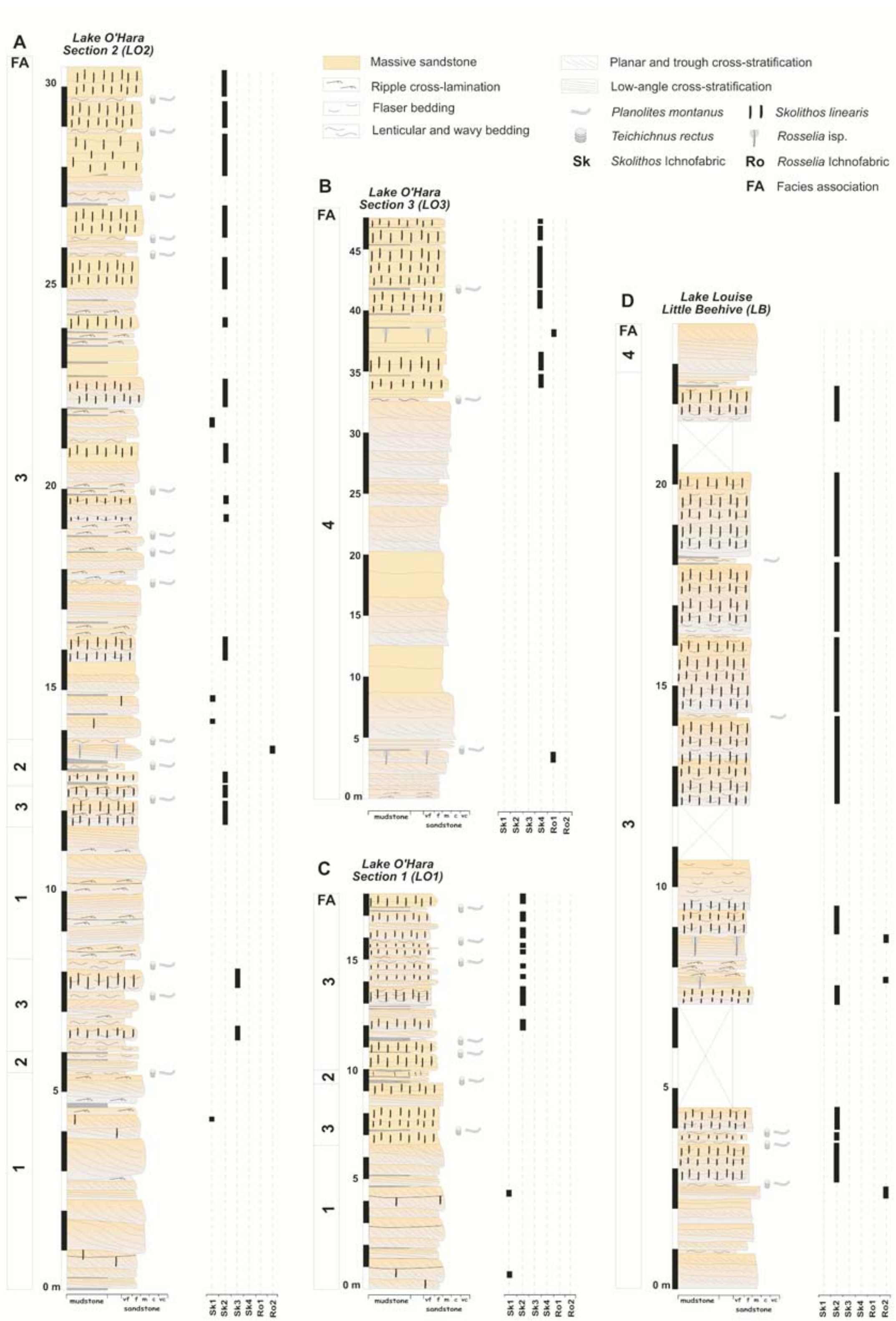

A
Lake O'Hara Section 2 (LO2)
B
Lake O'Hara Section 3 (LO3)
C
Lake O'Hara Section 1 (LO1)
D
Lake Louise Little Beehive (LB)
FA
mudstone
sandstone
vf f m c vc
Sk1 Sk2 Sk3 Sk4 Ro1 Ro2
Massive sandstone
Ripple cross-lamination
Flaser bedding
Lenticular and wavy bedding
Planar and trough cross-stratification
Low-angle cross-stratification
Planolites montanus
Skolithos linearis
Teichichnus rectus
Rosselia isp.
Sk Skolithos Ichnofabric
Ro Rosselia Ichnofabric
FA Facies association

Figure 2

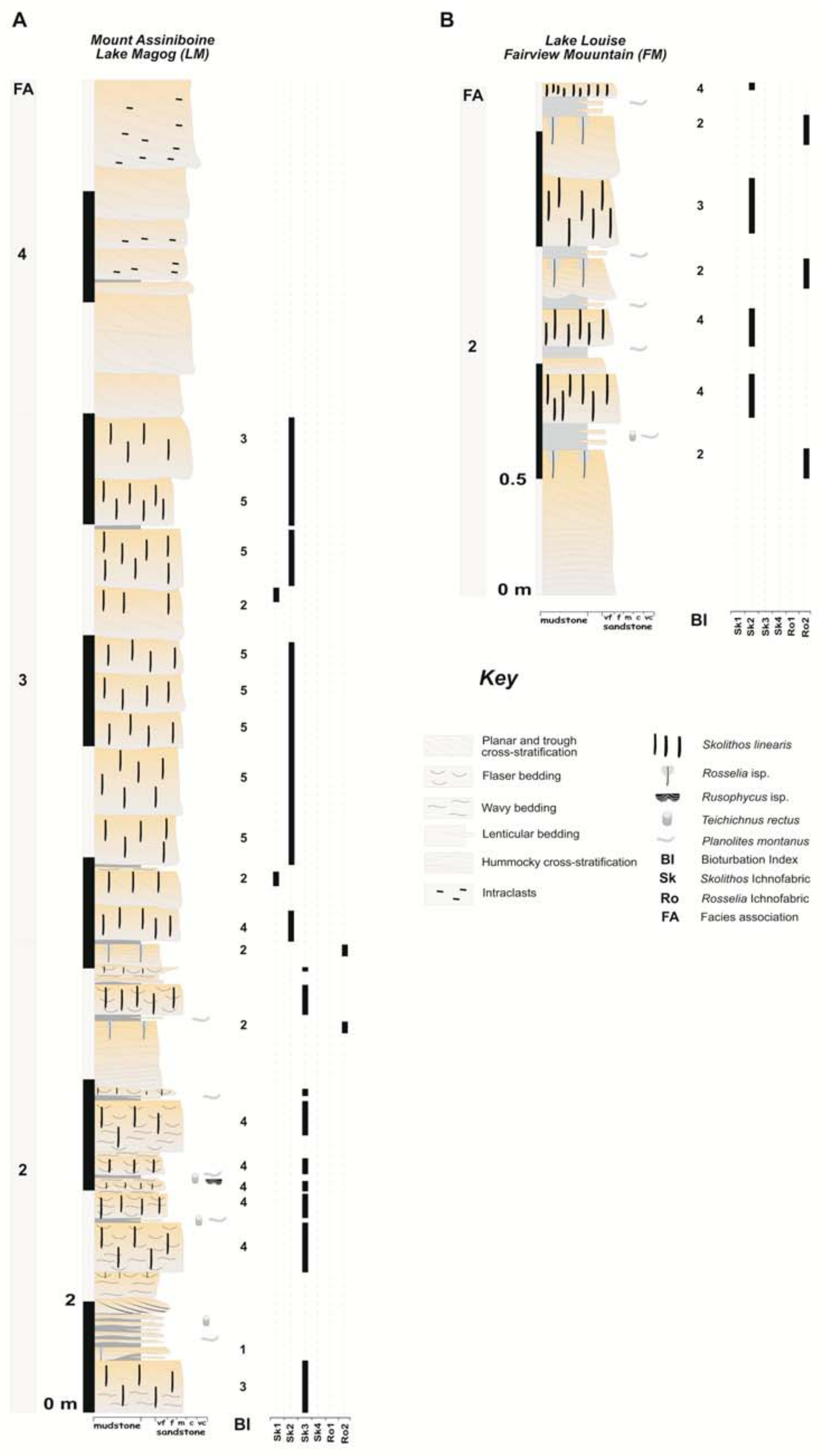

A
Mount Assiniboine
Lake Magog (LM)
FA
4
3
2
2
0 m
mudstone
vf f m c vc
sandstone
BI
Sk1
Sk2
Sk3
Sk4
Ro1
Ro2
B
Lake Louise
Fairview Mouuntain (FM)
0.5
Key
Planar and trough cross-stratification
Flaser bedding
Wavy bedding
Lenticular bedding
Hummocky cross-stratification
Intraclasts
Skolithos linearis
Rosselia isp.
Rusophycus isp.
Teichichnus rectus
Planolites montanus
BI Bioturbation Index
Sk Skolithos Ichnofabric
Ro Rosselia Ichnofabric
FA Facies association

Figure 3

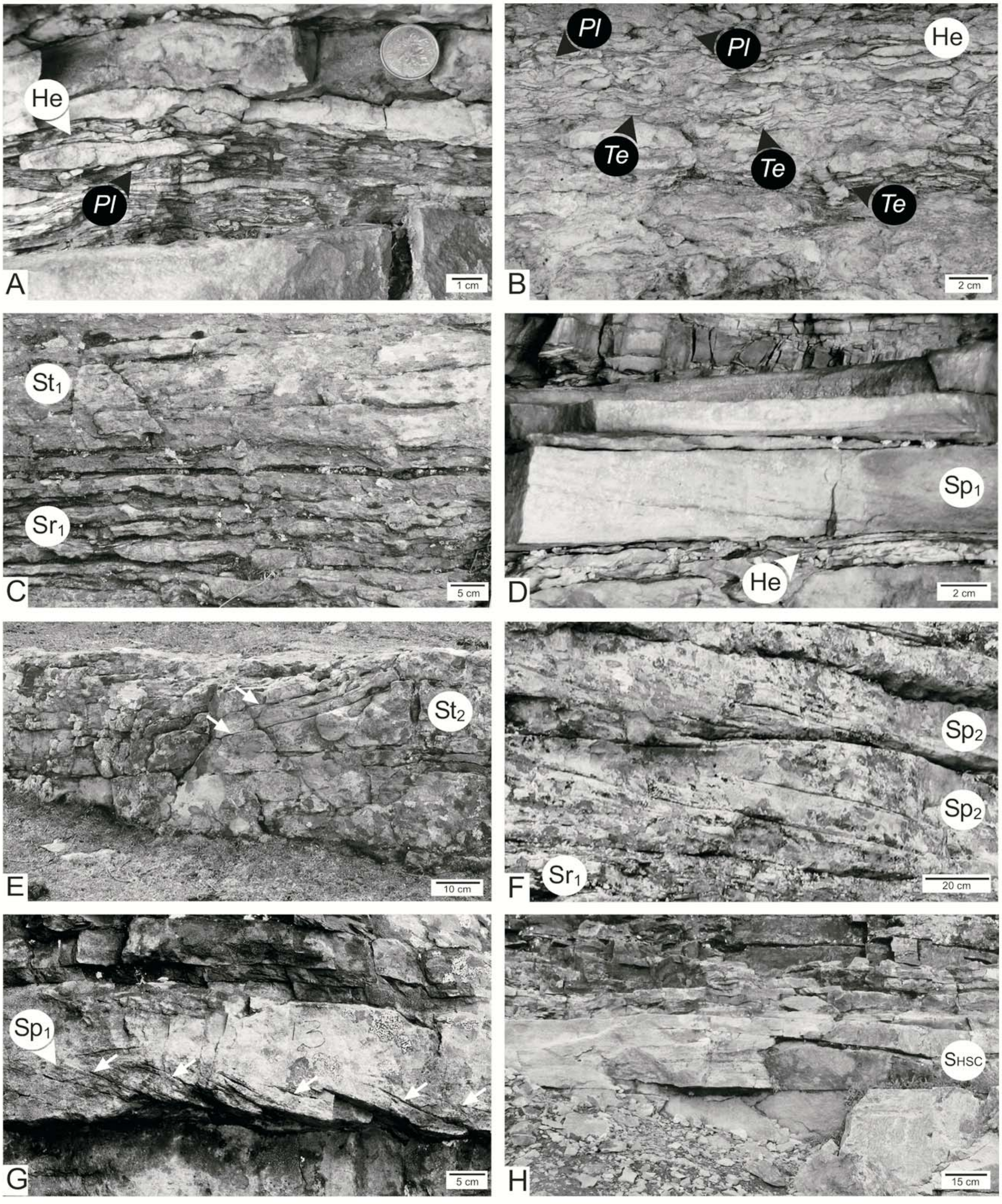

He
Pl
A
1 cm
Pl
Pl
He
Te
Te
Te
B
2 cm
St1
Sr1
C
5 cm
Sp1
He
D
2 cm
St2
E
10 cm
Sp2
Sp2
Sr1
F
20 cm
Sp1
G
5 cm
SHSC
H
15 cm

Figure 4

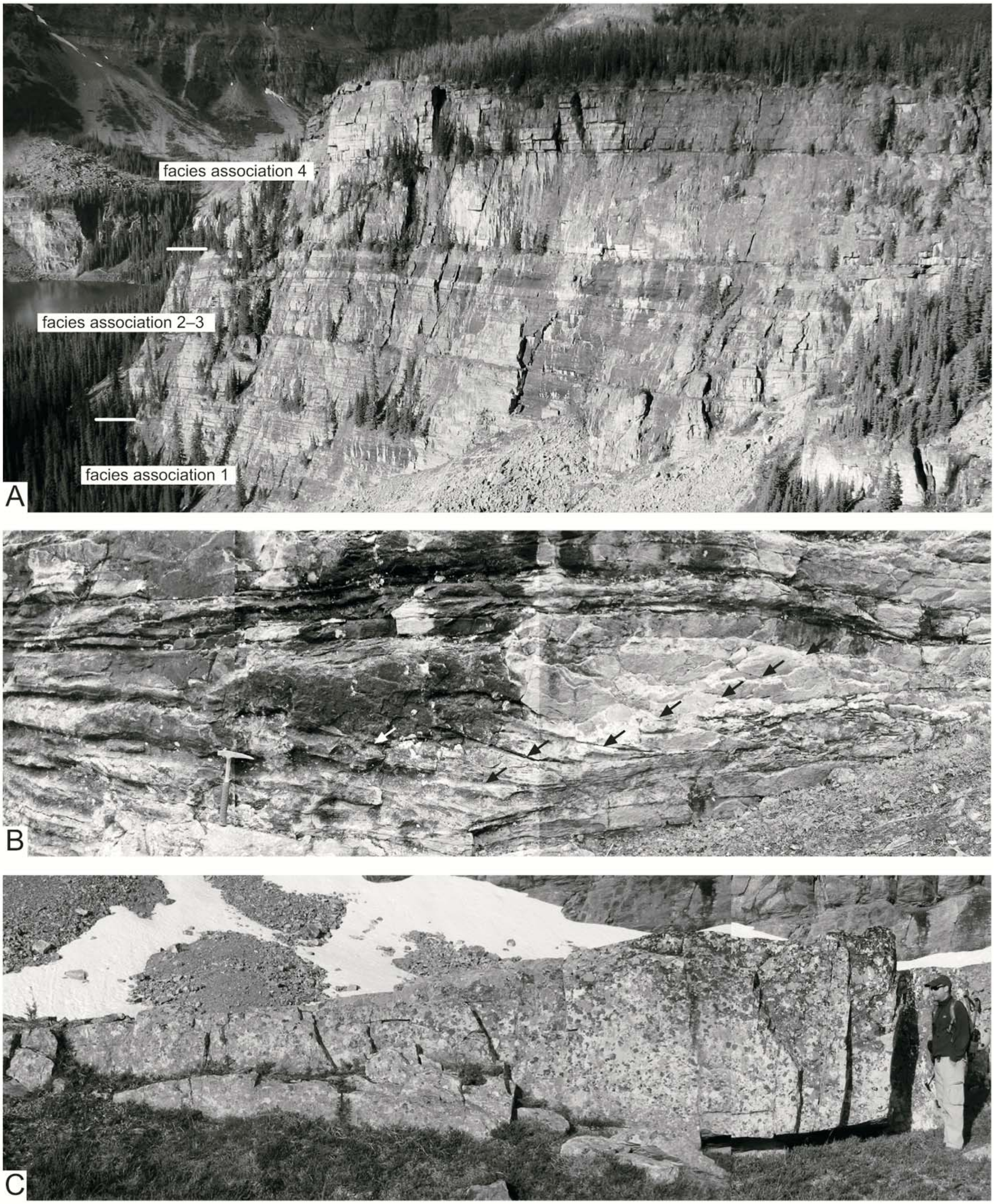

facies association 4
facies association 2–3
facies association 1
A
B
C

Figure 5

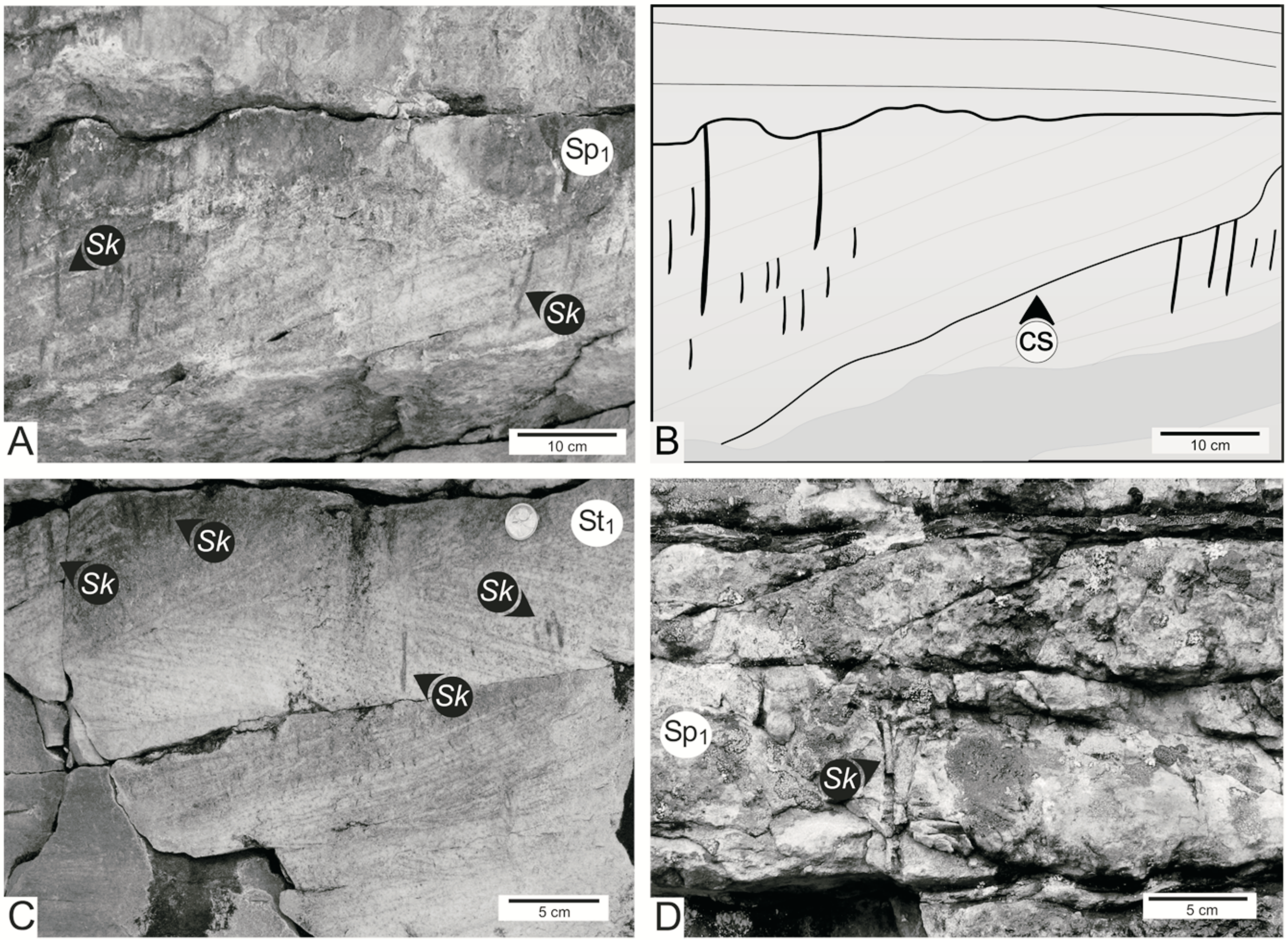


Figure 6

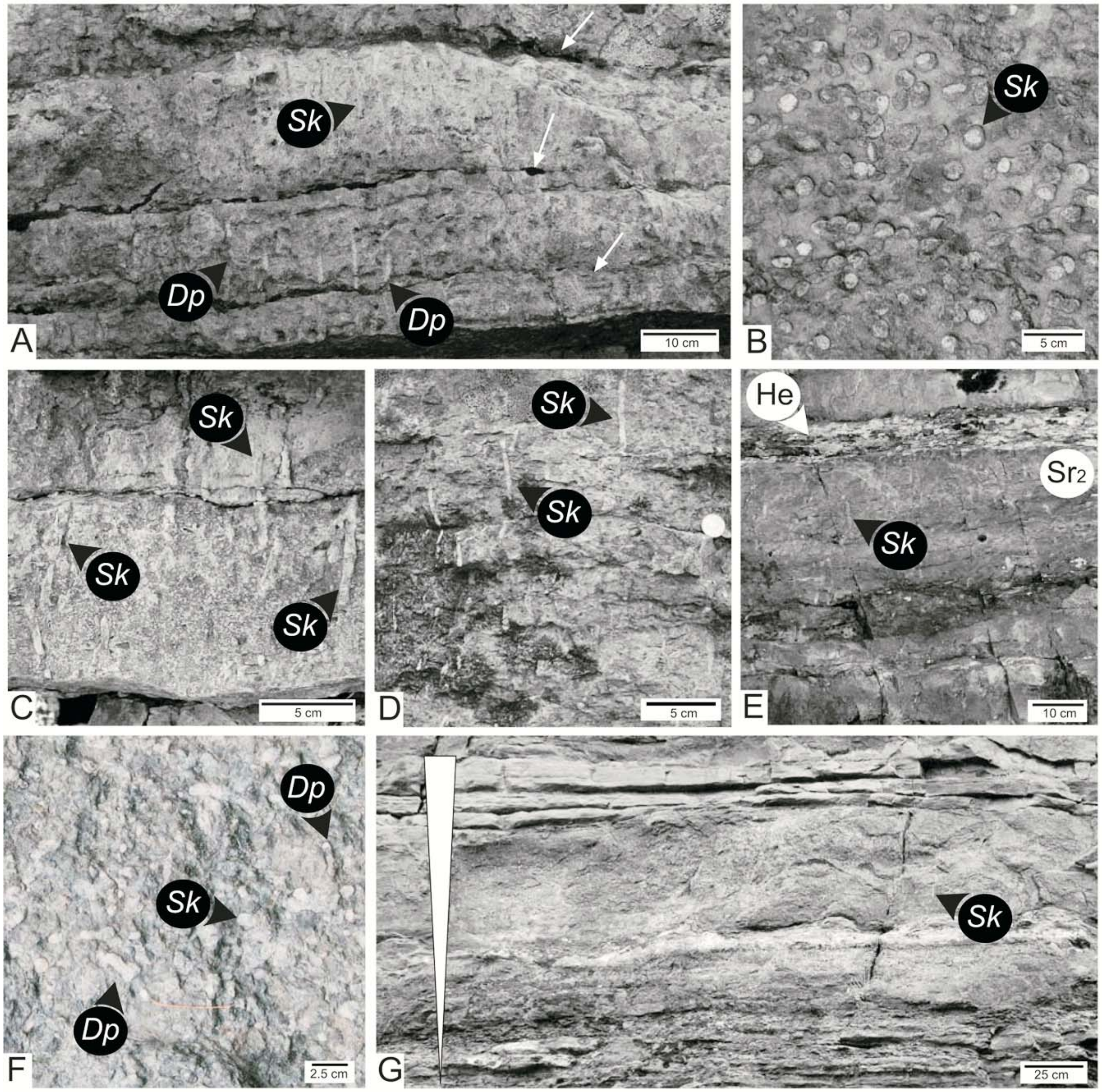

Sk
Dp
Dp
A
10 cm
Sk
B
5 cm
Sk
Sk
Sk
C
5 cm
Sk
Sk
D
5 cm
He
Sr2
Sk
E
10 cm
Dp
Sk
Dp
F
2.5 cm
Sk
G
25 cm

Figure 7

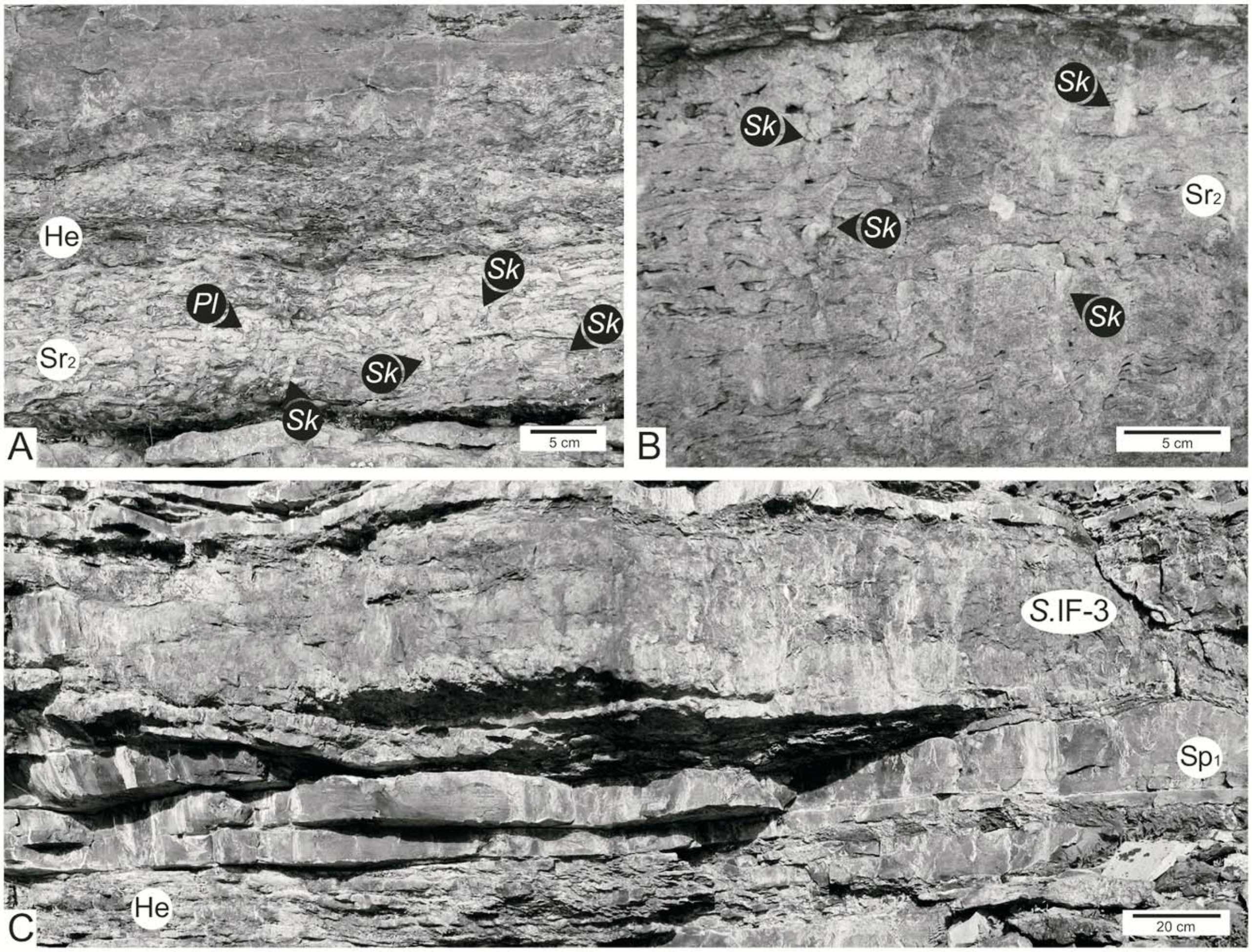


Figure 8

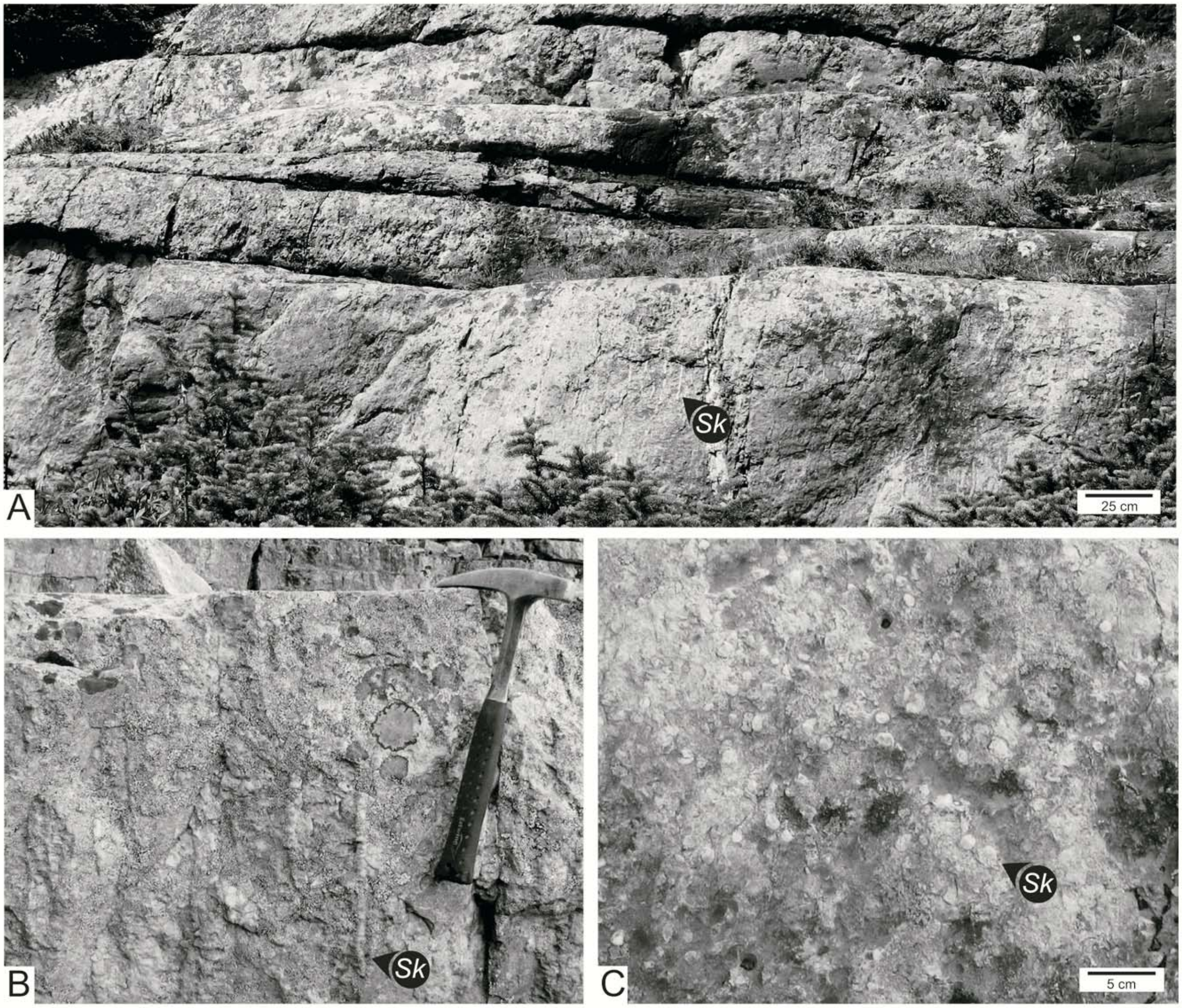


Figure 9

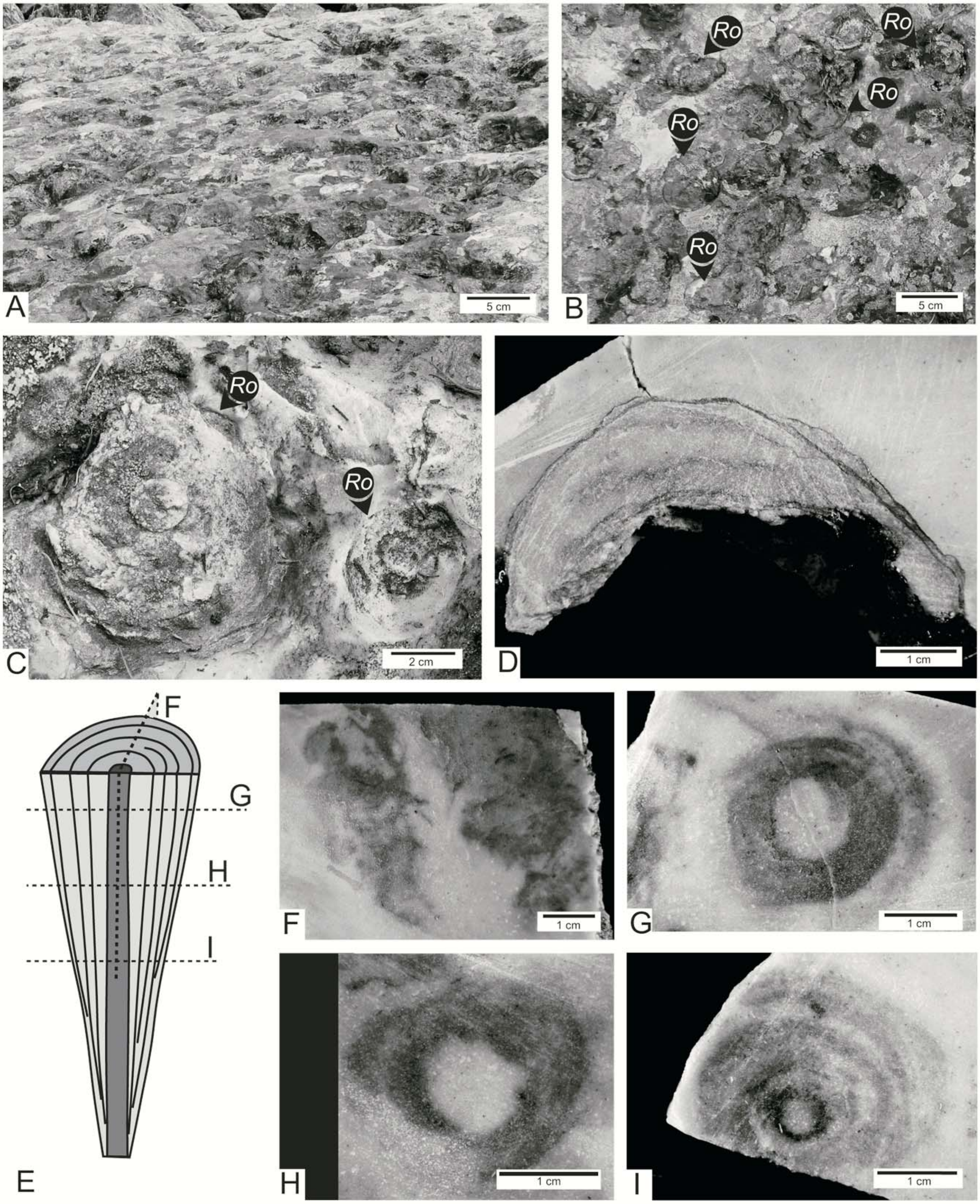


Figure 10

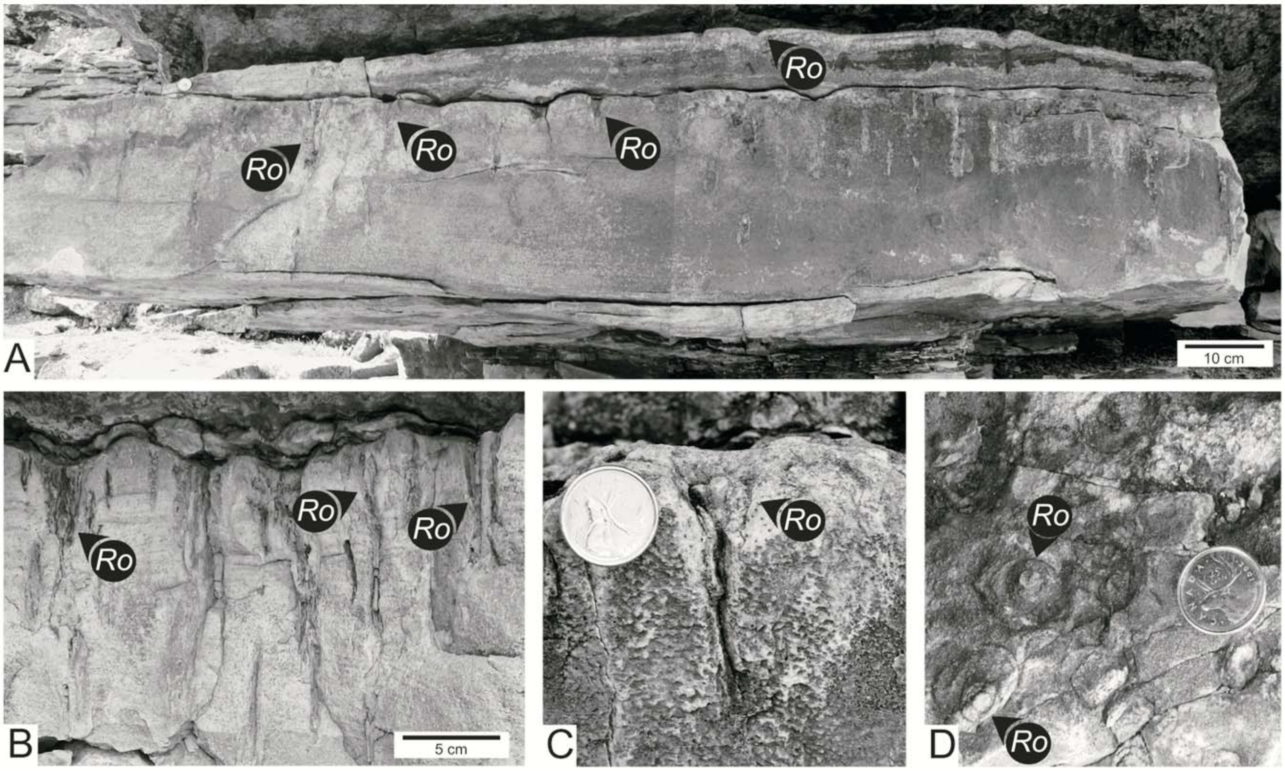
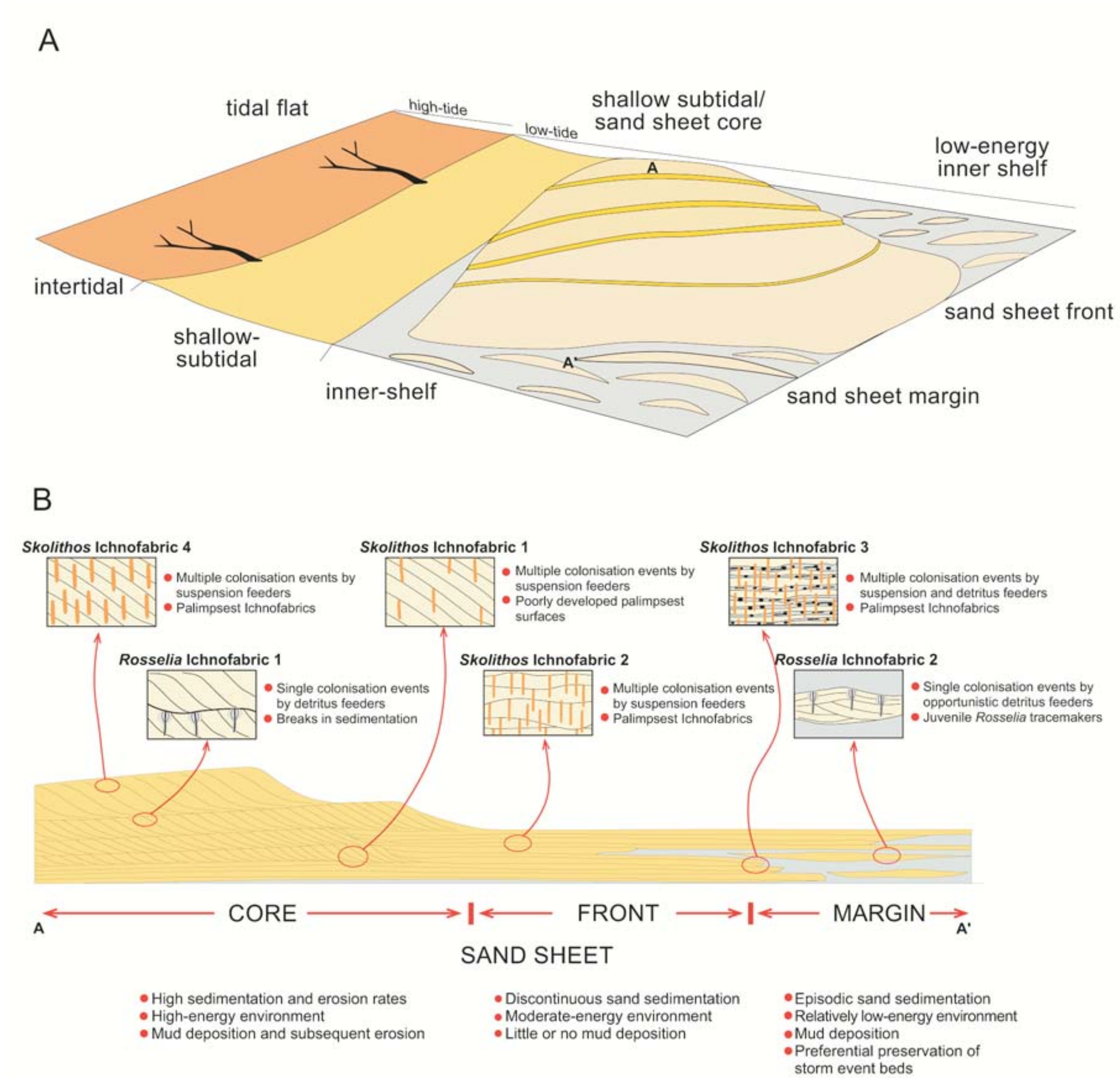


Figure 11



A
tidal flat
high-tide
low-tide
shallow subtidal/
sand sheet core
low-energy
inner shelf
A
intertidal
shallow-
subtidal
sand sheet front
A'
inner-shelf
sand sheet margin
B
Skolithos Ichnofabric 4
Multiple colonisation events by suspension feeders
Palimpsest Ichnofabrics
Skolithos Ichnofabric 1
Multiple colonisation events by suspension feeders
Poorly developed palimpsest surfaces
Skolithos Ichnofabric 3
Multiple colonisation events by suspension and detritus feeders
Palimpsest Ichnofabrics
Rosselia Ichnofabric 1
Single colonisation events by detritus feeders
Breaks in sedimentation
Skolithos Ichnofabric 2
Multiple colonisation events by suspension feeders
Palimpsest Ichnofabrics
Rosselia Ichnofabric 2
Single colonisation events by opportunistic detritus feeders
Juvenile Rosselia tracemakers
A
CORE
FRONT
MARGIN
A'
SAND SHEET
High sedimentation and erosion rates
High-energy environment
Mud deposition and subsequent erosion
Discontinuous sand sedimentation
Moderate-energy environment
Little or no mud deposition
Episodic sand sedimentation
Relatively low-energy environment
Mud deposition
Preferential preservation of storm event beds

Figure 12

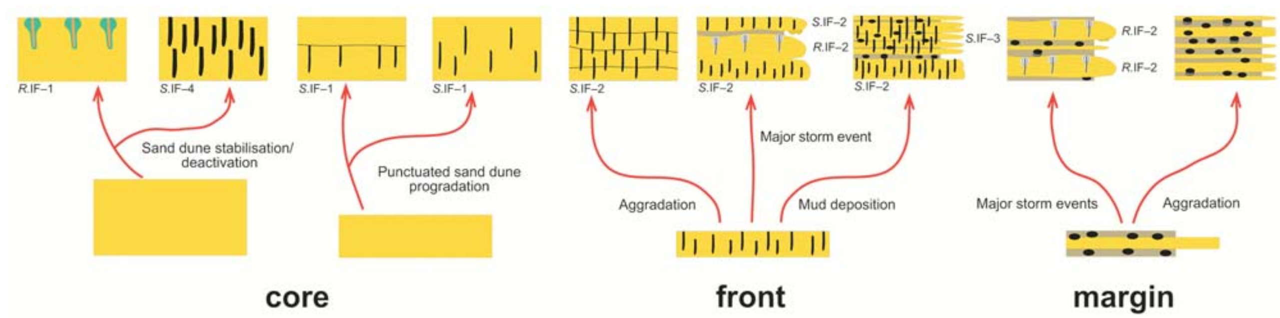

R.IF–1
S.IF–4
S.IF–1
S.IF–1
S.IF–2
S.IF–2
S.IF–2
R.IF–2
S.IF–2
S.IF–3
R.IF–2
R.IF–2
Sand dune stabilisation/ deactivation
Punctuated sand dune progradation
Major storm event
Aggradation
Mud deposition
Major storm events
Aggradation
core
front
margin

Figure 13

CHAPTER 5

Sand monsters

Subtidal sandbody architecture and ichnology in the Early Cambrian Gog Group of western Canada: Implications for an integrated sedimentologic-ichnologic model of tide-dominated shelf settings

ABSTRACT

Transgressive sandstones of the Lower Cambrian Gog Group of the southern Canadian Rocky Mountians were deposited on the broad, low-relief and low-gradient, tide-dominated continental shelf that rimmed almost contiguously the margin of Laurentia. Five types of compound cross-stratified sandstone are distinguished based on foreset geometry, sedimentary structures and internal heterogeneity. These represent five broad categories of subtidal sandbodies: (1) compound-dune fields; (2) sand sheets; (3) sand ridges; and (4) patchy dunes.

Compound-dune fields are characterised by sigmoidal and planar cross-stratified sandstone in coarsening- and thickening-upward packages. Both flood- and ebb-oriented cross-stratification is present. Compound dune deposits are mostly non-bioturbated or locally contain representatives of the *Skolithos* ichnofacies, but are intercalated with intensely bioturbated sandstones illustrating the archetypal *Cruziana* ichnofacies.

Sand-sheet complexes, also composed of compound dunes, cover more extensive subtidal areas and comprise three adjacent subenvironments: core, front and margin. The core is characterised by medium to thick tabular beds of planar and trough cross-stratified and type 2 compound cross-stratified sandstone. The front, where not intensively bioturbated, is characterised by type 3 compound cross-stratified sandstone with sporadically intercalated thin-bedded, ripple cross-laminated sandstone and mudstone.

The margin comprises interbedded very thin- to thin-bedded, ripple cross-laminated sandstone and mudstone, hummocky cross-stratified sandstone and, locally type 5 compound cross-stratified sandstone. Sand-sheet deposits exhibit clear trends in trace-fossil distribution along the sediment transport path, from non-bioturbated beds in the core to pipe rock comprising the *Skolithos* ichnofacies at the front, and a depauperate *Cruziana* ichnofacies at the margin.

Tidal sand ridges are large elongate sandbodies characterised by type 4 compound cross-stratified sandstone exhibiting large sigmoid-shaped reactivation surfaces. Coarsening- and thickening-upward successions are common. Sand ridges display clear ichnologic trends perpendicular to the axis of the ridge, with no bioturbation or a poorly developed *Skolithos* ichnofacies in the core, a depauperate *Cruziana* ichnofacies in lee-side deposits, and a *Cruziana* ichnofacies at the margin. Tidal bars are not present in the Gog Group but are differentiated from tidal ridges. While both migrate by means of lateral accretion, the former occur in association with channels while the latter do not. Because tidal bars tend to occur in brackish-water marginal-marine settings, their ichnofaunas are typically of low diversity, representing a depauperate *Cruziana* ichnofacies.

Patchy dunes developed on sand-starved areas of the shelf and their deposits are characterised by type 5 compound cross-stratified sandstone. They typically lack trace fossils, but the interfingering muddy deposits are intensely bioturbated by a high-diversity fauna recording the *Cruziana* ichnofacies.

The variety of sandbody types in the Gog Group reflects varying sediment supply and location on the inner continental shelf. Trace-fossil distribution in these tide-dominated sand bodies and adjacent sediments is mostly controlled by an interplay of substrate mobility, grain size, turbidity, water-column productivity, and sediment organic matter. Salinity is a critical factor in marginal-marine locations but played no role in this region of the shelf.

INTRODUCTION

Planar and trough cross-stratification is ubiquitous in tide-influenced successions recording bedload deposition by subaqueous dunes. Dunes are large-scale flow-transverse bedforms which represent a distinct entity abruptly separated from smaller ripples which have spacing generally less than 0.6 m. They function as a resistant element to the flow, and migrate under shear stress imparted on the sediment surface by the moving fluid.

Dunes are grouped into two broad categories, simple and compound (Ashley, 1990). Simple dunes do not have superimposed bedforms larger than ripples. By contrast, a compound dune, formerly called a sandwave, is composed of smaller dunes moving on the stoss and/or lee side of a larger one. The migration and deposition of superimposed dunes result in compound cross-stratification. This dune combination was difficult to explain in terms of flow parameters. Allen (1980) developed a model that involved periodically reversing currents, and predicted the internal structure for a range of current strengths and velocity asymmetries. However, this explanation has lacked confirmation from well-studied modern and ancient examples (Dalrymple & Choi, 2007). On the other hand, it may be that the presence of more than one bedform may simply be a function of available substrate space between dune crests and time for growth and migration, which can be seen conceptually as “nested” boundaries layers (Ashley, 1990). Hence, successively smaller dunes are stable at local boundary layers within the larger one. Despite the common occurrence of dunes and bars there is no consensus on a unifying terminology or a systematic classification for both relatively thick sets of cross-stratified sandstones and sandbodies.

Also, understanding of the ichnology of tide-dominated systems lags behind that of wave-dominated environments (e.g. Pemberton & MacEachern, 1997), as it has been focused on brackish-water environments, such as estuaries and bays(e.g. MacEachern & Pemberton, 1994; MacEachern & Gingras, 2007), tide-dominated deltas (e.g. MacEachern *et al*., 2005; McIlroy, 2007), tidal flats and associated subtidal areas (e.g. Mángano *et al*., 2002; Mángano & Buatois, 2004a,b), and tidally influenced and modulated shoreface settings (Dashgard et al., 2009, 2011). However, the ichnology of shelf tidal sandbodies has hardly been explored.

The Lower Cambrian Gog Group of the southern Rocky Mountains of western Canada is some one thousand metres thick, and records three successive shelf packages involving a range of subtidal environments. We describe the attributes and architecture of compound-cross stratified sandstone bodies contained in this well-exposed unit and propose a classification of the major types of shallow shelf sandbodies. In addition, we integrate sedimentologic data with ichnologic attributes, thereby providing a more robust facies model for subtidal sandbodies.

GEOLOGIC SETTING

Most siliciclastic shallow-marine continental shelf facies of Early Cambrian age share a remarkable similarity in the extraordinary large quantity of sand by comparison to their younger counterparts (Schumm, 1968; Dalrymple et al., 1985; Cant & Hein, 1986; McKie, 1993; MacNaughton et al., 1997). Land plants were virtually absent before the Silurian, which favoured development of extensive subaerial dune fields and braided fluvial systems (Rainbird et al., 1997; Davies & Gibling, 2010). Reworking by transgressive episodes and flooding of sandy coastal deposits contributed to the flux of large amounts of sediment from the continent to the shelf (Simpson & Eriksson, 1990).

Most of these Cambrian units are believed to have been deposited under the influence of strong tidal currents, because coastal facies locally contain diagnostic features, such as herringbone cross-stratification, lenticular/wavy/flaser bedding, double mud drapes, and tidal bundles. It has been argued that the effects of tides were much greater on Cambrian continental shelf areas, because the presumed closer position of the Moon to the Earth increased tidal forces (Hein, 1982). Also, Cambrian continental shelves were wide shallow platforms which would have amplified semi-diurnal tides (Clarke & Battisti, 1980), as well as having the potential for tidal resonance (Willis, 2005). The Gog Group, based on the dominance of unidirectional-current deposits, is interpreted to have been deposited on a tide-dominated shelf (Hein, 1982; Desjardins et al., 2011).

The Gog Group was part of an extensive sand belt that rimmed almost contiguously the continental margin of Laurentia just after the break-up of Rodinia. It was deposited on a broad, low-relief and low-gradient continental shelf under high accommodation rates driven by thermal subsidence and global sea-level rise, the ‘Cambrian Transgression’. Sediment was transported from the land surface comprised of Precambrian rocks of the Canadian Shield and its present-day extension beneath the western plains (Mountjoy & Aitken, 1963).

STUDY AREA

In age, the Gog Group is late Early Cambrian (Series 2), deposited during the Bonnia−Olenellus trilobite Biozone. Outcrops of this unit are widely and almost continuously distributed along the Main Ranges of the Rocky Mountains, from Mount Assiniboine northwards. In the southern Rocky Mountains, the Gog Group unconformably overlies deep-water shale and sandstone of the Neoproterozoic Hector Formation, which is the uppermost unit of the Miette Group (Fig. 1). The contact represents a major unconformity between Precambrian and Phanerozoic strata (Aitken, 1969), and records the transition from a syn-rift to post-rift tectonic setting. The Gog Group in the study area is formally subdivided into four units, in ascending order: the Fort Mountain, Lake Louise, St. Piran, and Peyto formations (Hein & McMechan, 1994; Desjardins et al., 2011). Desjardins et al. (2011) subdivided the St. Piran Formation into four members: Lake O'Hara, Lake Oesa, Moraine Lake and Wiwaxy Peaks members (Figs 2 and 3A).

In the environmental framework for tidal shelves adopted by Desjardins et al. (2011), the position of the wave-bases serves to separate three main environmental zones: (1) outer shelf, below storm wave base; (2) inner shelf, above storm wave-base and below fairweather wave-base; and (3) shallow subtidal above fairweather wave base and below low-tide line, comprising the shoreface of common usage in wave-dominated settings. The intertidal area lies landward of the shallow-subtidal environment (Fig. 4).

The basal Fort Mountain Formation is a coarsening-upward succession dominated by non-bioturbated sandstone composed of mainly tabular, cross-stratified sets (Fig. 3B) deposited in a shallow-subtidal environment. This unit is gradationally overlain by the Lake Louise Formation, which comprises intercalated, thin- to medium-bedded sandstone, siltstone and mudstone deposited in a low-energy inner-shelf setting (Figs 3C and 5A). The contact between the Lake Louise and St. Piran formations is also gradational. The contact between the Lake O'Hara Member and Lake Oesa Member of the St. Piran Formation is a regional unconformity (Desjardins et al., 2010, 2011).

The Lake O'Hara Member records sedimentation in an inner-shelf to shallow-subtidal environment (Figs. 3D and 5A). The Lake Oesa Member represents deposition in an intertidal setting. Inner-shelf sedimentation is dominant the lower and middle parts of the Moraine Lake Member (Fig. 3E), until a return to shallow-subtidal conditions in its uppermost part (Fig. 5B). The Wiwaxy Peaks Member is dominated by inner-shelf and shallow-subtidal deposits (Fig. 3F and 5B). The capping limestone and dolomite unit, the Peyto Formation, represents a reduction of siliciclastic sediment input (Hein, 1987; Aitken, 1997).

COMPOUND CROSS-STRATIFIED SANDSTONES

The distinction between two types of subaqueous sandbodies—tidal bars and compound dunes—was established by Dalrymple and Choi (2007), who noted that compound dunes migrate by means of forward accretion, and that thickness of the cross-stratified set and grain size increase upwards. By contrast, tidal bars are elongated, are oriented oblique to the flow, and migrate by means of lateral accretion. In these, cross-stratified set thicknesses thins upwards, and grain sizes fines upwards. Because Dalrymple and Choi focused on the fluvio-marine transition, they did not include a further type of flow-oblique barform which is the tidal sand ridge (Snedden & Dalrymple, 1999). These are characterised by thickening- and coarsening-upward lateral-accretion deposits. They develop on the open shelf, in contrast to tidal bars which occur within or between channels. In addition, an additional sandbody type can be called sand sheets, which represent large areas of the shelf covered by compound dunes of relatively low relief. These dunes decrease in size down the sediment transport path (Belderson et. al, 1982). Their deposits are characterised by a succession of coarsening- and thickening-upward packages. Also, in sand-starved areas of the shelf, patchy or isolated dunes may develop. Thus, five main types of subtidal sandbodies can be broadly discriminated: (1) compound-dune fields; (2) sand sheets; (3) tidal sand ridges; (4) patchy dunes; and (5) tidal bars. Five types of compound cross-stratified sandstone in the Gog Group represent the first four of these sandbodies (Table 1).

Type 1 compound cross-stratified sandstone

Description

Lenticular, 0.5–1.5 m thick, fine- to medium-grained compound cross-stratified sandstone typically exhibits a relatively sharp, planar to concave base and a generally undulating top (Fig. 6A–D). Distinctive foresets and bottomsets are present (Fig. 6C). Foresets are composed of 1–30 cm thick, cross-laminated sandstone divided by two orders of reactivation surfaces. First-order reactivation surfaces are sigmoidal, concave-up discontinuities. At the bottomsets, these discontinuities tend to merge, and are mantled by intercalated very thin- to thin-bedded, rippled cross-laminated sandstone and mudstone. In the sandstone beds delineated by the first-order discontinuities, subordinate reactivation surfaces truncate internal laminae. Locally thin mudstone laminae are present within the foresets. Scattered horizontal burrows belonging to *Planolites beverleyensis* occur in bottomsets (Fig. 7A). Cross-lamination within foresets dips in the same direction as reactivation surfaces. Rare ripple cross-laminae is present in bottomsets dip in the opposite direction. Locally, opposite cross-bedding directions is present in superimposed beds (Fig. 8A). This type of compound cross-bedded sandstone occurs amalgamated with others of similar characteristics. Commonly an overlying bed merges laterally into the cross bed of the one below through the intervening sigmoidal discontinuity (Fig 6A, B). Thus, beds have a lenticular geometry. Type 2 compound cross-stratified sandstone beds are also commonly interbedded (Fig. 8B).

Type 1 deposits occur in a 30 m interval in the Wiwaxy Peaks Member of the St. Piran Formation, exhibiting an overall thickening-upward trend. They gradationally overlie intervals composed of interbedded thin- to medium-bedded, fine-grained sandstone containing a diverse ichnofauna composed of *Rusophycus* isp., *Cruziana* isp., *Palaeophycus* isp., *Planolites montanus*, *Phycodes* isp. and *Helmintoidichnites tenuis*.

Interpretation

This type of compound cross-stratified sandstone records periodic migration and deposition of straight- to slightly sinuous-crested compound dunes under moderate asymmetric tidal currents. Small dunes on the stoss side of a large dune migrate over the crest and down lee face where they deposit their sediment as cross- and planar-laminated foresets. First-order reactivation surfaces are carved by the migration of a superimposed dune on the lee side (Dalrymple, 1984; Nio & Yang, 1991). Second-order reactivation surfaces are related to erosion by a subordinate opposite flow. Rippled bottomsets indicate the expected decrease of current strength at the toes of these bedforms. Mudstone laminae record periods of dune inactivity. This type of compound cross-stratification is similar to Type IV A of Allen (1980). The amalgamation of two overlying beds through sigmoidal-shaped discontinuities suggests that the overlying compound dune overtakes and buries the underlying one (Nio & Yang, 1991).

The lack of bioturbation in the sandbody indicates rapid bedform migration under a high-energy regime. The restriction of the deposit-feeder trace *Planolites* isp. to the bottomsets suggests very short-term colonisation windows (*sensu* Pollard *et al*., 1993). Clay and flocculated mud recorded by the mud drapes may have restricted the development of a suspension-feeding community. The occurrence of a diverse ichnofauna in the interbeds indicates a fully marine environment.

Type 2 compound cross-stratified sandstone

Description

This type consists of laterally continuous, 0.5–2 m thick, medium- to coarse-grained compound cross-stratified sandstone. Its lower and upper contacts are sharp and more or less horizontal (Fig. 9A, B). Sharp, mostly evenly spaced, planar surfaces within the foreset divide thin- to medium-bedded, wedge-shaped, planar cross-stratified sandstone. Mudstone drapes are rare. Cross-laminae dip in the same direction as internal discontinuities. Bioturbation is absent. This type of cross-stratification commonly occurs as individual units intercalated between other types of cross-stratified beds (Figs 8A and 10A) in the Wiwaxy Peaks, Lake O'Hara and Moraine Lake members, especially type 1, or with tabular medium-bedded planar cross-stratified sandstone.

Interpretation

Type 2 records deposition of large straight-crested compound dunes which migrate under asymmetrical tidal currents. Small- to medium-size straight-crested dunes on the stoss side migrate over the crest and down the lee side of the larger developing planar foreset surfaces and wedge-shaped beds during forward accretion. Thin mudstone drapes at the foresets indicate suspension fall-out during periods of dune inactivity, but are rarely preserved. Overlying sharp-based, tabular, medium-bedded planar cross-stratified sandstone records vertical accretion (Dalrymple, 1984). The absence of bioturbation suggests a shifting substrate under high-energy conditions which prevented the development of colonisation windows.

Type 3 compound cross-stratified sandstone

Description

More or less tabular, 0.3–1 m thick, fine- to medium-grained compound cross-stratified sandstone has lower and upper boundaries that are sharp, undulating and erosive (Fig. 11A, B). Each bedset is composed of wedges of thin- to medium-bedded, low-angle and planar cross-stratified, fine- to medium-grained sandstone bounded by gently inclined, slightly erosive surfaces. These internal discontinuities dip in the same direction as the laminae within individual cross-stratified beds. Mud drapes are rare. Bed thickness within each set generally increases upwards. Locally In places these surfaces are concave-upwards or sigmoidal, and cross-stratified sandstone merges at its top into intercalated rippled cross-laminated sandstone and mudstone with rare *Planolites montanus* and *Teichichnus rectus* (Fig. 7B, C). In some beds scattered vertical burrows belonging to *Skolithos linearis* are present (Fig. 7D). Elsewhere they are intensively bioturbated by *Skolithos linearis* and *Diplocraterion parallelum* (Fig. 7E) developing the ichnofabric referred to as pipe rock (Desjardins *et al*., 2010a). Type 3 sandstone bodies are recognized only in the Lake O'Hara Member.

Interpretation

Type 3 was deposited as slightly sinuous-crested, compound dunes that formed under asymmetric tidal currents. Small- to medium-size dune trains migrate on the stoss side of a larger dune, over the crest and down the lee side, depositing cross-stratified beds. Concave-upward, sigmoidal surfaces suggest periods of strong erosion at the lee side (Nio & Yang, 1991). Relatively horizontal amalgamated tabular beds suggest vertical accretion (Dalrymple, 1984). Mudstone drapes reflect periods of dune inactivity and suspension fall-out. Occurrence of ripple cross-laminated sandstone and mudstone in between bedsets records deposition at the toes of the compound dune (Allen, 1980). Thick packages consisting of this type of deposit indicate development over large areas of the inner shelf.

When current speeds dropped below the threshold for sediment motion, subaqueous dunes became inactive and colonisation windows developed at the foresets and topsets of these bedforms, allowing bioturbation by *Skolithos linearis* producers. The low degree of bioturbation that characterises these deposits most likely reflects single colonisation events related to short-term windows, in contrast to occasionally developed dense pipe rock which records longer term colonisation windows and multiple colonisation events. *Planolites montanus* and *Teichichnus rectus* reflect the activity of deposit feeders in mud-rich bottomsets.

Type 4 compound cross-stratified sandstone

Description

This type comprises 2–6 m thick, fine- to coarse-grained compound cross-stratified sandstone units (Fig. 12A, B). Their bases and tops are slightly undulating. Sigmoidal-shaped discontinuities divide the compound bed set into thin- to very thick-bedded, planar, trough and herringbone cross-stratified sandstone, with common reactivation surfaces and mud-drapes, interbedded with very thin- to thin-bedded, ripple cross-laminated sandstone and mudstone. Commonly, medium- to thick-bedded cross-stratified sandstone passes laterally along the sigmoidal reactivation surface to interbedded thin- to medium-bedded, ripple cross-laminated sandstone, lenticular-bedded sandstone, and mudstone. The large sigmoidal structures are often indistinct. Stacked coarsening- and thickening-upward trends, such as those displayed in this type of deposit, are observed in intervals up to 6 m thick. The dip directions of the large sigmoidal-shaped discontinuities are commonly at right angles to the cross-bedding above and below it.

The trace fossil content is mainly restricted to horizontal and sub-horizontal traces in interbedded sandstone and mudstone facies belonging to *Cruziana* isp., *Dimorphichnus* isp., *Planolites montanus*, *Palaeophycus* isp., *Phycodes* isp., and *Rusophycus* isp. (Fig. 13A, B). Local *Skolithos linearis* is the only vertical form present in cross-stratified beds. Type 4 sandstone bodies occur only in the Wiwaxy Peaks Member.

Interpretation

Type 4 is interpreted to record small to large dunes and compound dunes on a sand ridge in which the compound cross-stratified sets are a consequence of obliquely lateral accretion which leads to sigmoidal beds (Snedden & Dalrymple, 1999). Paleocurrents above and below lateral accretion surfaces suggest bedload transport oblique to the strike of the ridge. Bioturbated very thin- to thin-bedded sandstone and mudstone intervals reflect lower energy off the tidal ridge and the diverse trace-fossil assemblage suggests fully marine conditions and abundant food supply. The relatively rare occurrence of *Skolithos* in cross-stratified sandstone suggests higher energy-conditions and generally short-term colonisation windows.

Type 5 compound cross-stratified sandstones

Description

This comprises lenticular, 01–0.5 m thick, low-angle cross-stratified, fine-grained sandstone packaged by sigmoidal-shaped reactivation surfaces. These beds occur intercalated within very thin- to thin-bedded sandstone and mudstone (Fig. 14A–D). Each bed offlaps or pinches out against a discontinuity. Aggrading topsets are locally present the updip portions, delineated by relatively planar discontinuities on (Fig. 14A, B). In the downdip portions, foresets grade laterally into intensively bioturbated, very thin- to thin-bedded, intercalated ripple cross-laminated, lenticular-bedded sandstone and mudstone. These contain *Cheiichnus gothicus*, *Conostichus* isp., *Cruziana* isp., *Diplichnites* isp., *Halopoa* isp., *Helminthopsis* isp., *Dimorphichnus* isp., *Palaeophycus* isp., *Phycodes* isp., *Planolites* isp., *Rhizocorallium* isp., *Rusophycus jenningsi*, *R. pectinatus*, *Teichichnus rectus* and *Trichophycus venosus* (Fig. 12C–G). Cross-lamination dips in same direction as sigmoidal-shaped surfaces. These units occur as isolated sandstone lenses in mudstone-dominated facies of the Lake Louise Formation.

Interpretation

Type 5 is interpreted as the result of deposition of straight- to slightly sinuous-crested, small- to medium-sized dunes. Sigmoidal erosive surfaces record erosion of a faster migrating dune that overtakes and buries the one below. Amalgamation of beds suggests vertical accretion. Intensively bioturbated bottomsets by mainly deposit-feeding faunas suggest prolonged periods of dune inactivity and suspension fall-out in a fully marine environment. Their occurrence within mudstone-dominated facies suggests a sand-starved setting. Thus, they represent an isolated dune patch on a mud-rich area of the inner shelf.

DISCUSSION

Most of the classic criteria for recognizing tidal deposits (e.g. herringbone cross-stratification, lenticular/wavy/flaser bedding, double mud drapes, and tidal bundles) are based on observations from intertidal areas where tidal action may be the only significant physical process (Nio & Yang, 1991). However, sedimentation on shelves differs from that on coastal areas as the former are largely influenced by: (1) rotary tides (i.e., lacking slack-water period); (2) less distinct ebb/flood tidal cyclicity; and (3) storms, oceanic currents and other types of offshore processes (Suter, 2006). Thus, many of the diagnostic criteria for tidal sedimentation are not directly recognizable in shelf deposits (Johnson & Baldwin, 1996; Willis, 2005).

Despite the continually changing strength of tidal currents the direction of peak velocity speed -ebb or flood- of the mean spring tidal currents indicates the net sand transport path (Johnson *et al.*, 1982). Occasionally, the spring tidal current may be the only one above the threshold of sediment movement, and thus bedforms may appear stationary for most of the time and be prone to bioturbation. Mud laminae in this case do not represent a single period of slack-water, but of dune inactivity.

Compound dunes are a recurrent bedform in tide-dominated sandy shelves (e.g. Belderson *et al.*, 1982; Berné *et al.*, 1988). However, they are also common in estuaries (e.g. Dalrymple *et al.*, 1990; Dalrymple & Rhodes, 1995), deltas (e.g. Willis, 2005; Carmona *et al.*, 2009), bays (Boyd *et al.*, 2008), fluvial channels (e.g. Bridges, 1985), ooid shoals (e.g. Rankey *et al.*, 2006), and offshore areas affected by strong oceanic currents (e.g. Flemming, 1980).

Similar types of sandbodies have been classified under different names (Table 2), which can inhibit understanding. We recognize five distinctive types of compound cross-stratified sandstone, interpreted as having been deposited as part of different types of subtidal sandbodies. We consider most of them to fall into five broad categories (Fig. 14): (1) compound-dune fields (Types 1 and 2); (2) sand sheets (Types 2 and 3); (3) sand ridges (Type 4); (4) patchy dunes (Type 5); and (5) tidal bars, which although not recognized in the Gog Group, are also a component in many modern and ancient examples (e.g. Dalrymple *et al.*, 2003; Dalrymple & Choi, 2007).

Compound-dune fields

Sandbodies in the Eocene Baronia Formation of Spain, the source of the tidal bar model of Mutti *et al.* (1985) and similar to Type 1 deposits in the Gog Group, have been reinterpreted as compound dunes within a strait or seaway (Dalrymple *et al*., 2003; Dalrymple & Choi, 2007; Olariu *et al*., 2008). This is supported by the fact that the dip directions of internal discontinuities are the same as that of the cross-stratified sets, and that the unit displays thickening- and coarsening-upward trends, both features suggestive of dune migration by forward accretion. This contrasts with tidal-bar deposits which are characterised by a thinning- and fining-upward trend, due to the fact that their lowermost parts comprise coarser channel deposits. Modern tidal bars are flow-oblique barforms, and migrate by means of lateral accretion (Dalrymple *et al.*, 2003, Dalrymple & Choi, 2007). The main components of compound-dune fields are sigmoidal cross-stratified sandstone beds which converge down-dip tangentially into thin-bedded horizontal bottomsets. These units are grouped together into bedsets also with sigmoidal geometry. They are interpreted to accrete vertically and migrate by forward accretion in the direction of the local predominant flow.

Sand sheets

Although they both consist of compound dunes, a sand sheet (*sensu* Stride *et al.*, 1982) differs from a compound-dune field because the former covers extensive areas of the shelf and shows a decrease of bedform sizes down the sediment transport path, while the latter comprises dunes of similar sizes. For example, the North Sea is characterised by sand sheets and ridges that are unrelated to the adjacent shoreline and migrate under the influence of strong tidal currents. There, tidal-current transport paths extend over hundreds of square kilometres, thereby developing a suite of bedforms that decrease in size in conjunction with a reduction in flow strength, which typically accompanies an increase in water depth. Bedforms are arranged along the sediment transport path in three regions: (1) a zone of large compound dunes; (2) a zone of small compound dunes; and (3) a zone of sand ripples. Within the zone of large compound dunes, sand supply is abundant and tidal sand ridges can develop (Belderson *et al.*, 1982). In the areas of highest energy, sand ribbons, furrows and gravel lags are commonly developed (Stride *et al.*, 1982).

Desjardins *et al.* (2010a) proposed a facies model for sand-sheets and characterised the deposits of three main subenvironments: core, front and margin. Facies at the core comprise medium- to thick-bedded, cross-stratified sets of planar, trough and compound cross-stratified sandstone. These deposits are the coarsest-grained in the Gog Group, and represent shallow areas under the strongest currents. The front is characterised by thin- to medium-bedded, planar and compound cross-stratified sandstone. The margin, off the flanks of the complex, comprises interbedded very thin- to thin-bedded, rippled cross-laminated sandstone and mudstone, hummocky cross-stratified sandstone, and local thin- to medium-bedded, planar cross-stratified sandstone. The areas of highest energy are recorded by a very coarse-grained sandstone and conglomerate lag capping cross-stratified sandstone.

Type 2 compound cross-stratified sandstone associated with tabular beds of planar cross-stratified sandstone are interpreted as deposits of large straight-crested compound dunes recording frontal and vertical accretion. This type of deposit is a common element at the core of sand sheets associated with high-energy areas under constant sediment supply.

On the other hand, type 3 compound cross-stratified sandstone is interpreted to have been deposited as compound dunes in the sand-sheet front environment. The development of intervals more than 10 m thick composed entirely of these deposits suggests that conditions of flow strength were stable for long periods of time, coupled with balanced sediment supply and accommodation. Relatively uniform thickness of bedsets and amalgamation without occurrence of different facies suggest evenly spaced compound-dune trains of similar heights. Although, sand-sheet front deposits are often riddled with *Skolithos linearis*, those areas of the front characterised by type 3 compound cross-stratified sandstones containing only scattered *Skolithos* burrows, suggesting that colonisation windows for the development of an extensive suspension-feeding community were frequently closed as a result of a constantly shifting substrate (Desjardins *et al.*, 2010a). The presence of sporadic hummocky cross-stratification in sand-sheet margin deposits suggests storm reworking (Cheel & Leckie, 1993).

Tidal sand ridges

Sand ridges are elongated sand bodies that are larger and geographically stable in contrast to dunes. Their heights are typically more than 20% of the water depth and lengths in the order of 10 km (Snedden & Dalrymple, 1999). Ridges are generally oriented at an oblique angle to the strongest current. In modern shelves, they typically occur in groups, with spacing of individuals in the order of 250 times the water depth, but solitary ridges do occur (Snedden & Dalrymple, 1999). Channel-like features between ridges are called swales (Dyer & Huntley, 1999). Snedden and Dalrymple (1999) noted that, regardless the nature of the source of the currents that generate them, be they waves or tides, all ridges share similar morphological characteristics. The only significant difference they noted is that tidal ridges are commonly longer than storm-built ridges.

Ridge genesis and maintenance is explained by the ‘Huthnance process’ (Huthnance, 1982; Hulsher *et al.*, 1993). Where a current meets a bathymetric irregularity on the sea floor, it tends to accelerate as it flows over the up-current side due to flow constriction and then weaken over the crest and down the lee side. The up-current side is eroded and sand is deposited in the lee side causing upward growth and down-current migration. If sufficient sand is available, the process continues until an equilibrium profile is reached, at which point upward growth ceases and widening of the feature begins on the lee side (Suter, 2006). Four conditions are required for sand-ridge formation: (1) an initial irregularity, commonly a transgressed coastal sandbody (e.g. Swift & Field, 1981; Penland *et al.*, 1988; Snedden & Dalrymple, 1999; Snedden *et al.*, 1999; Posamentier, 2002); (2) sufficient sand supply; (3) a current capable of moving sand; and (4) sufficient time for the sand to be moulded into a ridge. Tidal sand ridges in the North Sea were formed when glacioeustatic lowstand deposits were reworked by tidal currents (Belderson *et al.*, 1982). Sand ridges in the East China Sea also developed during the Pleistocene–Holocene transgression. These overlie deltaic deposits (Berné *et al.*, 2002), and become younger towards the present location of the Yangtze River due to continued transgression (Liu *et al*., 1998).

The internal structure of tidal sand ridges consists of smaller scale cross-stratified beds deposited mainly on the lee sides. If the sand ridge is associated with a transgression coupled with decreased sediment supply, its deposits are characterised by a fining- and thinning-upward trend, as current speeds decrease with an increasing water depth. However, smaller-scale thickening- and coarsening-upward intervals record progradation of dunes on the flank over lower-energy areas on the lee-side and in the swale in between ridges.

Type 4 compound cross-stratified bedsets are interpreted to record tidal sand ridges. This type of cross-stratification is formed by lateral accretion and oblique migration of an elongated sandbody on top of which migrated superimposed bedforms of different sizes. The coarsening-upwards intervals are related to deposition of large dunes over the crest and down the lee sides. Muddy areas off the ridges typically hosted a diverse ichnofauna.

Patchy dunes

These types of subtidal bedforms occur in patches of sand that has been mobilized by tidal currents under condition of very low sediment supply. They have not been described from modern settings, but are inferred from type 5 cross-stratified sandstones. This type of compound cross-stratification occurs as medium- to thick-bedded lenticular packages deposited as a sand-starved dune train. This type of deposit typically develops during transgressive phases as shallower water sands on the shelf are remobilized by tidal currents.

Tidal bars

Bars are longer lived than subaqueous dunes (Dalrymple & Rhodes, 1995). They occur as flow-transverse, oblique and longitudinally oriented bodies, commonly with dunes superimposed on them. Bars are thought to scale with flow width rather than flow depth as dunes do (Dalrymple & Rhodes, 1995).

Tidal bars are commonly developed within distributary channels, delta fronts and outer parts of estuaries (Dalrymple & Choi, 2007), but not on the shelf proper, because in offshore areas tidal currents are not focused by geomorphologic features. The migration of tidal bars, like tidal sand ridges, is slightly oblique, but in the direction of dominant current. Their stoss side is eroded by the dominant current, whereas deposition occurs on the opposite lee side. This leads to the preferential preservation of the down-current flank of the bar, where sedimentation is dominated by the subordinate current. As a result, the small cross beds within the large-scale lateral-accretion deposits are likely to be oriented in the direction of the regional weaker current (Dalrymple & Choi, 2007, fig. 29).

The lateral-accretion deposits of tidal bars are typically erosively based, due to the migration of the thalweg of the adjacent channel. Because the water depth and the current speed both decrease upwards from the thalweg towards the bar crest, bedset thickness thins upwards and grain size fines upward, except if fluid muds are developed in the channel bottom (Dalrymple *et al.*, 2003). This contrasts with tidal sand ridges in unconfined areas of the shelf.

Ichnologic trends in shelf tidal sandbodies

Ecological controls

Benthic faunas in tide-dominated complexes are mostly controlled by an interplay of (1) salinity, (2) substrate mobility, (3) water turbidity, (4) substrate type, (5) suspended organic matter, and (6) sedimented organic matter.

In the case of the Gog sandbodies, salinity fluctuation is not regarded as a control because emplacement took place in shelf settings under normal-marine conditions. However, salinity strongly impacts the nature of the resident ichnofaunas in brackish-water environments (e.g. Pemberton *et al*., 1982; Benyon *et al*., 1988). Tidal bars, which typically formed in restricted brackish-water settings (e.g. estuaries, bays), tend to contain low-diversity ichnofaunas dominated by trophic generalists, such as *Planolites* or *Teichichnus* (MacEachern & Pemberton, 1994; Mángano & Buatois, 2004a; MacEachern & Gingras, 2007). Also, depauperate trace-fossil suites are commonly present in tidal-bar or compound-dune field deposits emplaced in delta fronts, albeit alternating with intervals displaying taxa that are less tolerant of salinity fluctuations, such as *Phycosiphon* or *Chondrites* (e.g. MacEachern *et al*., 2005; Carmona *et al*., 2009).

Substrate mobility from bedform migration is a first-level factor because it essentially controls the duration of the colonisation window (Pollard *et al*., 1993). Under continuous migration, the colonisation window is closed or short term, preventing bioturbation or allowing burrowing by opportunistic organisms adapted to high-energy conditions, respectively (Desjardins *et al*., 2010a). Longer-term colonisation windows characteristic of discontinuous migration or dormant forms are conducive to more extensive bioturbation.

Water turbidity plays an important role in controlling trophic type (Buatois & Mángano, 2011). In particular, clogging by abundant clay and silt particles in suspension in the water column precludes the establishment of a suspension-feeding community (Gingras *et al*., 1998; MacEachern *et al*., 2005). Under conditions of extreme water turbidity, primary production can be severely affected resulting in a general impoverishment of both suspension and deposit feeders (Leithold & Dean, 1998).

Substrate, in terms of type (sand vs. mud), degree of consolidation (e.g. role of fluid muds) and amount of organic matter, impacts the benthic fauna. Some ichnotaxa tend to be restricted to certain types of substrate, such as *Skolithos* in sand and *Planolites* in heterolithic intervals. In turn, accumulation of fluid muds is quite common in tide-dominated settings, imparting a substrate stress by reducing boundary shear stress, which prevent benthic organisms to construct permanent structures or actively backfill tunnels (Schieber, 2003; MacEachern *et al*., 2005; Buatois & Mángano, 2011). Fluid-mud deposits are typically non-bioturbated or, more rarely, contains “mantle and swirl” biogenic structures (Schieber, 2003; Bhattacharya & MacEachern, 2009).

Environmental distribution

Trace fossil content of the Gog Group and comparison with other tidal deposits elsewhere allows ichnologic characterisation of subtidal sandbodies (Fig. 15). Sand-sheet deposits in the Gog Group exhibit predictable trends in trace-fossil distribution along the sediment transport path (Desjardins *et al*., 2010a). High-energy conditions due to continuous bedform migration, coupled with intense erosion and high sedimentation rates, commonly preclude bioturbation in the core of the sand sheet. In the sand-sheet front deposits, the presence of smaller bedforms resulting from discontinuous sand sedimentation was conducive to colonisation by *Skolithos linearis* producers in sandy substrates, illustrating the *Skolithos* ichnofacies. Overall, bioturbation intensity increases from the proximal to the distal core deposits, resulting in the common occurrence of *Skolithos* pipe rock in the latter. Ichnofabrics are composite (i.e. resulting from multiple bioturbation events), with vertical burrows penetrating from various colonisation surfaces, indicating multiple pauses in sedimentation. Sand-sheet margin deposits are characterised by alternating episodic sandstone sedimentation and mud deposition under relatively low-energy conditions. Mud-rich bottomsets contain a deposit-feeding fauna represented by *Planolites montanus* and *Teichichnus rectus*. Low-ichnodiversity even in the low-energy facies is attributed to soupy substrate conditions.

Compound dunes in the Gog are for the most part non-bioturbated or contain just a few *Skolithos linearis*, representing the *Skolithos* ichnofacies. Moderate to high sedimentation rates and erosion resulting from continuous and rapid bedform migration are deemed responsible for the scarce bioturbation. Bottomset deposits are locally bioturbated by *Planolites beverleyensis.* By contrast, intercalated intensely bioturbated deposits contain the archetypal *Cruziana* ichnofacies dominated by arthropod trace fossils (e.g. *Rusophycus* isp., *Cruziana* isp.), horizontal vermiform burrows (e.g. *Palaeophycus* isp., *Planolites montanus*, *Phycodes* isp.) and simple grazing trails (e.g. *Helmintoidichnites tenuis*). This ichnofauna reveals preferential preservation of mud in the bottomsets, low-energy conditions and more or less continuous colonisation windows. Ichnologic properties of compound dunes in the Baronia sandbody are similar to those in the Gog, and associated lower-energy deposits in the Baronia sandbody contain a diverse ichnofauna, indicative of the archetypal *Cruziana* ichnofacies (Olariu *et al*., 2008).

The sandy portion of patchy dunes tends to be non-burrowed, most likely as a result of high mud content in the water column, which may have prevented the establishment of the typical suspension-feeding faunas that are adapted to relatively high-energy settings. However, the interfingering muddy deposits display high ichnodiversity and are intensely bioturbated. With the exception of the simple facies-crossing form *Palaeophycus* isp., the ichnofauna consists of deposit-feeder trace fossils, produced by both arthropods (e.g. *Cheiichnus gothicus*, *Cruziana* isp., *Diplichnites* isp., *Dimorphichnus* isp., *Rusophycus jenningsi*, *R. pectinatus*) and worms (e.g. *Helminthopsis* isp., *Phycodes* isp., *Planolites* isp., *Teichichnus rectus, Trichophycus venosus*). This is consistent with continuous colonisation windows in a mud-dominated low-energy setting.

Sand ridges display clear ichnologic trends perpendicular to the axis of the ridge. Bioturbation is virtually absent in the cross-stratified beds that make up the core of the tidal sand ridge, and only scarce *Skolithos linearis* are present, clearly indicating closed to short-term colonisation windows linked to rapidly migrating bedforms. The lee-side deposits of sand ridges are characterised by increased heterogeneity as recorded by pervasive interfingering of muddy layers. These heterolithic deposits mark the transition from the *Skolithos* ichnofacies to a depauperate *Cruziana* ichnofacies, characterised by low-diversity suites dominated by *Planolites montanus* and *Teichichnus rectus*. Low-ichnodiversity and sparse bioturbation most likely reflect soupy substrates in connection with fluid muds. Off the sand ridge, mud-dominated heterolithic deposits contain an archetypal *Cruziana* ichnofacies, with abundant arthropod (e.g. *Cruziana* isp., *Dimorphichnus* isp., *Rusophycus* isp.) and worm (*Planolites montanus*, *Palaeophycus* isp., *Phycodes* isp.) trace fossils.

Trace fossil distribution in the Gog sandbodies demonstrates that, despite the complexities of these deposits, recurrent patterns are apparent. They add a further dimension to the ichnofacies gradients recognized for tide-dominated shorelines (e.g. Mángano *et al*., 2002; Mángano & Buatois, 1999, 2004a,b).

CONCLUSIONS

(1) The Lower Cambrian Gog Group comprises four types of large subtidal sandbodies encompassing compound-dune fields, sand sheets, sand ridges and patchy dunes. A fifth type, tidal bars, has not been recognized in the Gog.

(2) Compound-dune fields are characterised by type 1 and 2 compound cross-stratified sandstones grouped in coarsening- and thickening-upward packages.

(3) Sand-sheet complexes are also composed of compound dunes but distributed in three adjacent subenvironments: core, front and margin. The core of the complex is recorded by medium- to thick-bedded, tabular beds of planar and trough cross-stratified and type 2 compound cross-stratified sandstone. The front, if not intensively bioturbated, is characterised by type 3 compound cross-stratified sandstone with local occurrence of very thin-bedded, interbedded ripple cross-laminated sandstone and mudstone. The margin, off the flanks of the complex, comprises intercalated very thin- to thin-bedded, rippled cross-laminated sandstone and mudstone.

(4) Sand ridges are large, elongated sandbodies characterised by type 4 compound cross-stratified sandstone deposited by obliquely lateral accretion. Coarsening- and thickening-upward intervals are common.

(5) Patchy dunes develop on sand-starved areas of the shelf and their deposits are characterised by type 5 compound cross-stratified sandstone, encased in mudstone-dominated facies.

(6) Tidal bars differ from sand ridges, although both migrate by means of lateral accretion. Tidal bars are associated with channels, and their deposits display a thinning- and fining-upward trend.

(7) Different sandbody types on the same tide-dominated shelf have different ichnological properties, owing to variation in substrate type, sediment mobility and other environmental factors.

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Figure captions

Figure 1. Study area in western Canada. Geological map of the Bow Valley region of the southern Rocky Mountains showing the location of the studied outcrops. Pmi = Miette Group; l€gg = Fort Mountain, Lake Louise and lower St. Piran formations; u€gg = upper St. Piran and Peyto formations; €cp = Middle Cambrian platform carbonates; Qd = Quaternary. 1 = Lake Louise; 2 = Moraine Lake; 3 = Larch Valley; 4 = Lake O'Hara; 5 = Sink Lake; 6 = to Spiral Tunnels; 7 = to Calgary; 8 = to Jasper.

Figure 2. Composite stratigraphic section of the Gog Group in the Lake Louise–Lake O'Hara sector.

Figure 3. (A) Southern side of Wiwaxy Peaks and Mount Huber at Lake O'Hara showing position of normal faults and stratigraphic subdivisions. (B) Fort Mountain Formation at Lake O'Hara. (C) Type section of Lake Louise Formation on northwestern flank of Fairview Mountain, near western end of Lake Louise. (D) Lake O'Hara Member and lower St. Piran Formation at base of Mary Lake, near Lake O'Hara. (E) Tower of Babel

by the eastern end of Moraine Lake. (F) Western flank of Mount Temple above Moraine Lake.

Figure 4. Idealized bathymetric profile showing the main environmental settings recognized in the Gog Group.

Figure 5. Stratigraphic sections and interpreted sedimentary environments. (A) Composite type section of the Lake Louise Formation, and Lake O'Hara and Lake Oesa Members of the St. Piran Formation at Lake O'Hara. (B) Lake Oesa, Moraine Lake and Wiwaxy Peaks members of the St. Piran Formation at Lake Oesa, above Lake O'Hara. Modified from Desjardins *et al.* (2011).

Figure 6. Type 1 compound cross-stratified sandstone. (A) Two vertically superimposed sandbodies. (B) Tracing of bedding geometry of A showing lenticular geometry of lower dune resulting from erosion by overlying dune, whose deposits merge into the foresets of the underlying one. Heavier lines delineate bed boundaries. (C) Close-up of right side of lower dune in A. (D) Tracing of bedding geometry of A. Lines delineate first-order reactivation surfaces. Heavier lines delineate deeper erosion surfaces. Compound-dune field, Wiwaxy Peaks Member, Larch Valley.

Figure 7: (A) Bedding plane with *Planolites beverleyensis* (*Pl*) at bottomsets of Type 1 compound cross-stratified sandstones. Wiwaxy Peaks Member, Larch Valley. (B) *Planolites montanus* (*Pl*) and *Teichichnus rectus* (*Te*) in intercalated rippled cross-laminated sandstone and mudstone at bottomsets of Type 3 compound cross-stratified sandstone. Sandstone lenses have injection dykelets (Sy) extending downward from their soles. Lake O'Hara Member, Lake O'Hara. (C) As in B. (D) *Skolithos linearis* in topsets of Type 3 compound cross-stratified sandstone. (E) Pipe rock ichnofabric composed of

Skolithos linearis and *Diplocraterion parallelum*. Gog Group undivided, Mount Assiniboine.

Figure 8. (A) Type 1 cross-stratified sandstone exhibiting superimposed ebb- and flood-oriented cross-stratified beds. (B) Two coarsening- and thickening-upward packages composed of type 1 and 2 compound cross-stratified sandstone. White arrow points to boundary between two packages. Compound-dune field, Wiwaxy Peaks Member, Larch Valley.

Figure 9. (A) Type 2 compound cross-stratified sandstone. Compound-dune field. Wiwaxy Peaks Member, St. Piran Formation, Larch Valley. (B) Tracing of A. Heavier lines delineate reactivation surfaces.

Figure 10. (A) Type 2 compound cross-stratified sandstone overlain by tabular beds of planar cross-stratified beds. Sand-sheet complex core. Wiwaxy Peaks Member. Highway # 1 roadcut at Sink Lake. (B) Tracing of A. Heavier lines delineate boundaries between cross-stratified beds.

Figure 11. (A) Interval of thick-bedded, type 3 compound cross-stratified sandstone. Sand-sheet complex front, Lake O’Hara Member, Mary Lake, near Lake O’Hara. (B) Tracing of A. Heavier lines delineate boundaries between type 3 compound cross-stratified bed sets.

Figure 12. (A) Sand-ridge lateral-accretion deposits exhibiting very thick-bedded, type 4 compound cross-stratified sandstone. Wiwaxy Peaks Member, Highway #1 roadcut at Spiral Tunnels.

Figure 13. (A, B) Bed soles in mud-dominated heterolithic deposits intercalated with type 4 compound cross-stratified sandstone. Wiwaxy Peak Member, Spiral Tunnels. (A)

Palaeophycus isp. (*Pa*) and *Phycodes* isp. (*Ph*). (B) *Phycodes* and *Dimorphichnus*-like scratch marks (Sm). (C–G) Type 5 compound cross-stratified sandstone ichnofauna; bed soles in D–F. Lake Louise Formation. (C) Intercalated thin-bedded sandstone and mudstone containing relatively deep *Rusophycus* isp. (*Ru*) and local *Planolites montanus* (*Pl*) and *Palaeophycus* isp. (*Pa*). (D) *Cruziana* isp. (*Cr*), *Rusophycus* isp. (*Ru*) and *Phycodes* isp. (*Ph*). Lake O'Hara. (E) *Dimorphichnus* isp. (*Di*) and *Palaeophycus* isp. (*Pa*). Lake Louise. (F) *Trichophycus venosus* (*Tr*). Lake Louise. (G) *Conostichus* isp. (Co). Lake O'Hara.

Figure 14. Type 5 compound cross-stratified sandstone. (A) Bedset with paleocurrents directed towards the right. (B) Tracing of A, showing thinning of bedset towards the left. Heavier lines delineate bed boundaries. (C) Bedset with paleocurrents directed towards the left. (D) Tracing of C, showing the transition of cross-stratified beds to rippled bottomsets. Heavier lines delineate bed boundaries. Inner-shelf dune patch, Lake Louise Formation, Lake Louise.

Figure 15. Paleoenvironmental distribution of subtidal sandbodies in a tide-dominated shelf setting.

Figure 16. Integrated ichnologic and sedimentologic model of tidal sandbodies in a shelf setting.

Table captions

Table 1. Compound cross-stratified sandstone types and their properties in the Gog Group, Lower Cambrian, western Canada.

Table 2. Subtidal sandbody types and their characteristics. References for other terms for these types: (1) Boyd *et al.*, 2008; (2) Mutti *et al*., 1985; (3) Allen, 1980 *inter alia*; (4) Santisteban & Taberner, 1988; (5) Houthuys & Gullentops, 1988; (6) Rankey *et al.*, 2006; (7) Belderson *et al.*, 1982, Dyer & Huntley, 1999 *inter alia*; (8) Penland *et al.*, 1988; (9, 10) Dyer & Huntley, 1999; (11) Dalrymple, 1992. Locals in brackets under 'Environment' not recognized in the Gog Group.

5

Type	Bed scale	Internal geometry	Sand grain size	Foreset geometry	Mud laminae	Internal heterogeneity	Stratigraphic occurrence	Figure
Type 1–Sigmoidal	Medium to very thick	Lenticular	Fine to medium	Sigmoidal	Common	High	Wiwaxy Peaks Member	Figs 6A–D, 7A–B
Type 2–Planar	Thick to very thick	Tabular	Medium to coarse	Planar	None to rare	Low	Wiwaxy Peaks, Lake O'Hara and Moraine Lake members	Figs 7B, 8A–B, 9A, B
Type 3–Low-angle	Thick	Tabular	Fine to medium	Planar to sigmoidal	Rare to common	Low to moderate	Lake O'Hara Member	Fig. 10A–B
Type 4–Large-scale	Very thick	Lenticular	Fine to coarse	Sigmoidal	Abundant	Very high	Wiwaxy Peaks Member	Fig. 11A–B
Type 5–Lenticular	Thin to medium	Lenticular	Fine	Sigmoidal	Abundant	High	Lake Louise Formation	Fig. 12A–D

Sandbody type	Shape	Orientation	Bedforms	Packaging	Sand supply	Environment	Gog Group category	Other commonly used terms
Type A: Compound-dune field	Elongate to wide	Flow-transverse	Compound dunes, ripples	Thickening- and coarsening-upwards	Moderate to high	Shallow subtidal, inner shelf (delta front, bays)	Type 1: Sigmoidal	Tidal dune[1], tidal bar[2], sand wave[3], sand wave complex[4], tidal transverse bar[5], shoal[6]
Type B: Sand sheet	Wide	Flow-transverse	Simple and compound dunes, sand ridges, ripples	Thickening- and coarsening-upwards	Very high	Shallow subtidal, inner shelf	Type 2, 3: Planar, low-angle	
Type C: Tidal sand ridge	Elongate	Flow-oblique	Simple and compound dunes, ripples	Thickening- and coarsening-upwards	Moderate to high	Inner shelf (outer shelf)	Type 4: Large scale	Sand bank[7], shoal[8]
Type D: Dune patch	Elongate to wide	Flow-transverse	Simple dunes, ripples	Thickening- and coarsening-upwards	Very low	Inner shelf (outer shelf)	Type 5: Lenticular	Sand patch[7]
Type E: Tidal bar	Elongate	Flow-oblique	Compound dunes, ripples, channel-forms	Thinning- and fining-upwards	High to moderate	(Distributary channels, delta front, outer estuaries)	Not recognized in the Gog Group	Sand bank[9], sand ridge[10], elongate sandbar[11]

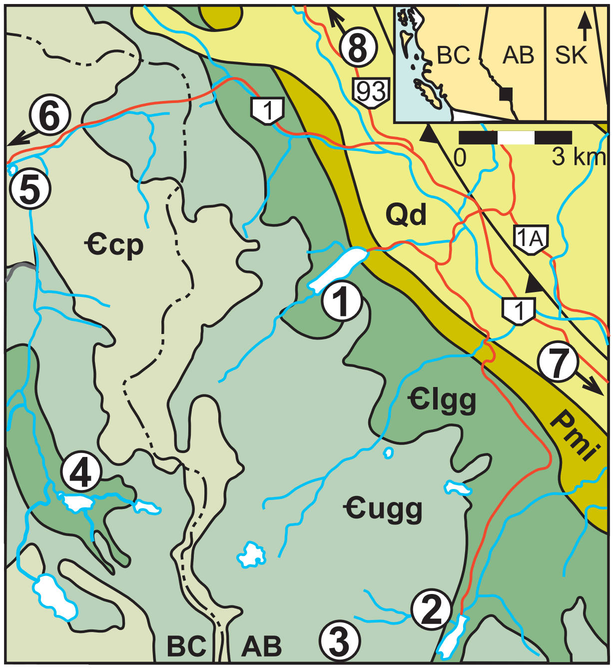


Figure 1

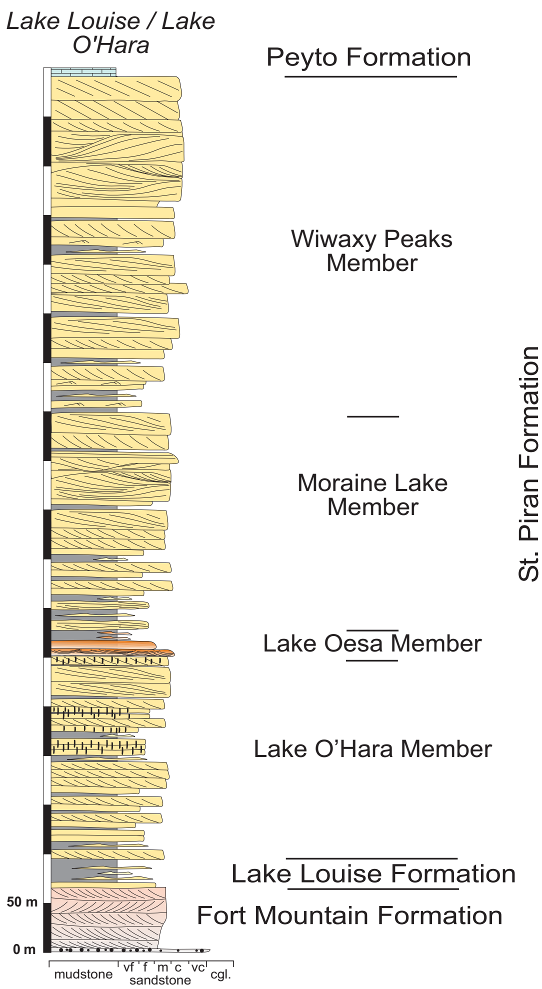
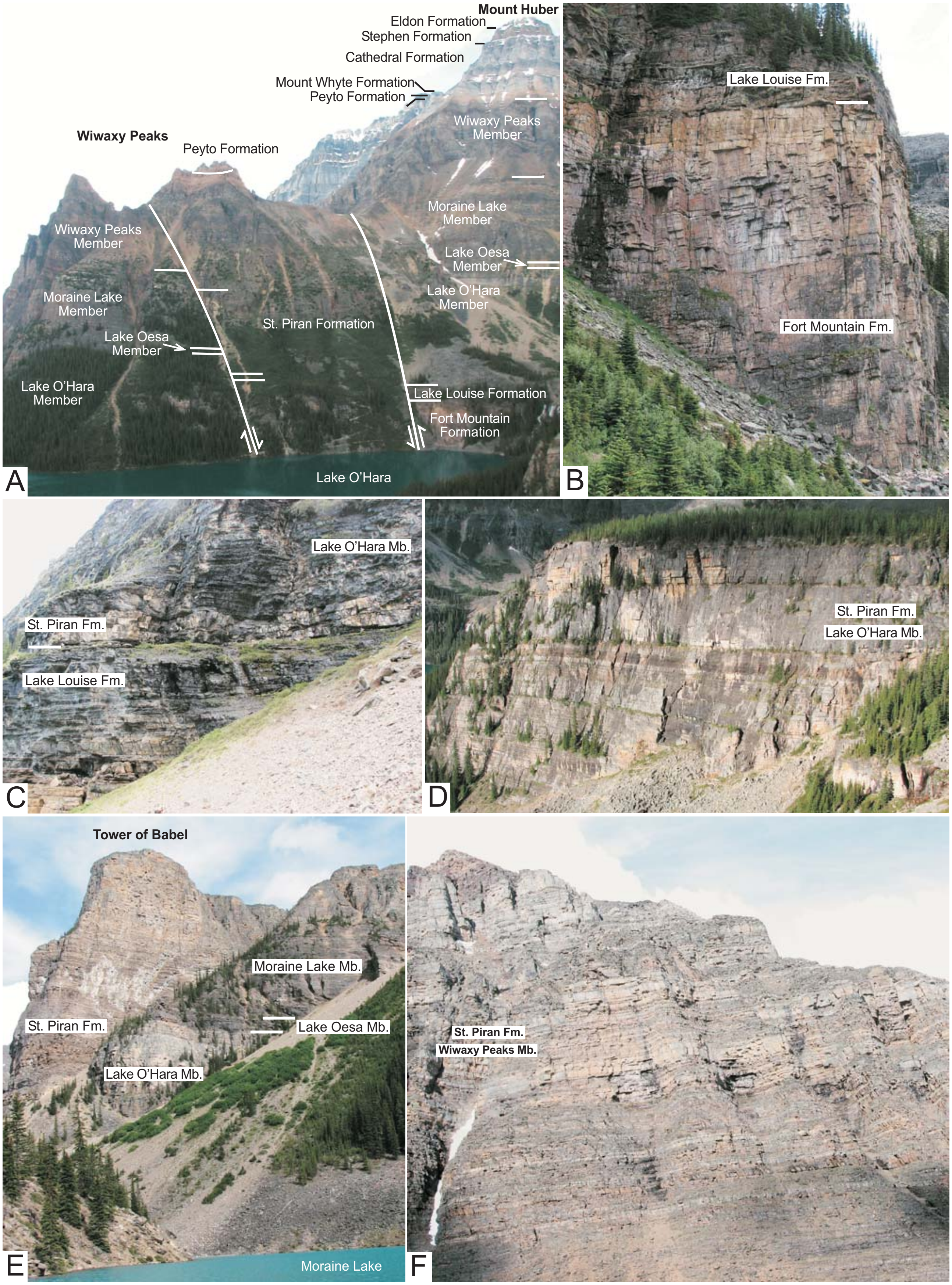

Lake Louise / Lake O'Hara
Peyto Formation
Wiwaxy Peaks Member
Moraine Lake Member
St. Piran Formation
Lake Oesa Member
Lake O'Hara Member
Lake Louise Formation
Fort Mountain Formation
50 m
0 m
mudstone
vf
f
m
c
vc
sandstone
cgl.

Figure 2



Mount Huber
Eldon Formation
Stephen Formation
Cathedral Formation
Mount Whyte Formation
Peyto Formation
Wiwaxy Peaks
Peyto Formation
Wiwaxy Peaks Member
Moraine Lake Member
Lake Oesa Member
Lake O'Hara Member
St. Piran Formation
Lake Louise Formation
Fort Mountain Formation
Lake O'Hara
A
Lake Louise Fm.
Fort Mountain Fm.
B
Lake O'Hara Mb.
St. Piran Fm.
Lake Louise Fm.
C
St. Piran Fm.
Lake O'Hara Mb.
D
Tower of Babel
Moraine Lake Mb.
St. Piran Fm.
Lake Oesa Mb.
Lake O'Hara Mb.
Moraine Lake
E
St. Piran Fm.
Wiwaxy Peaks Mb.
F

Figure 3

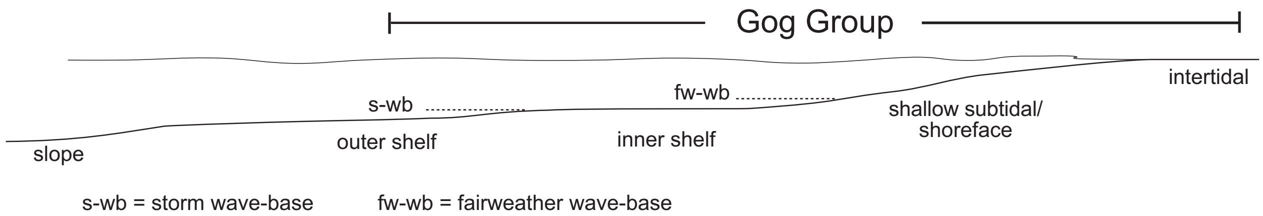

Gog Group
intertidal
s-wb
fw-wb
shallow subtidal/
shoreface
outer shelf
inner shelf
slope
s-wb = storm wave-base
fw-wb = fairweather wave-base

Figure 4

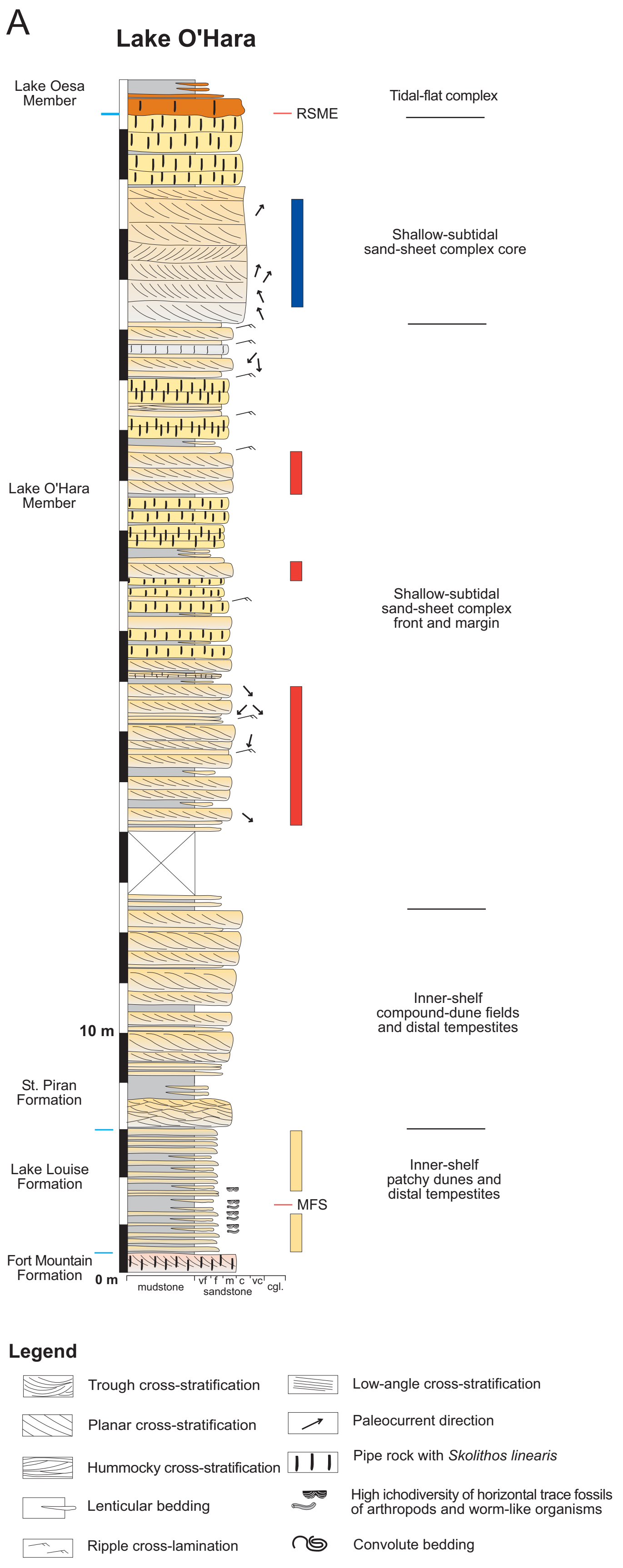

A
Lake O'Hara
Lake Oesa Member
RSME
Tidal-flat complex
Shallow-subtidal sand-sheet complex core
Lake O'Hara Member
Shallow-subtidal sand-sheet complex front and margin
Inner-shelf compound-dune fields and distal tempestites
10 m
St. Piran Formation
Lake Louise Formation
Inner-shelf patchy dunes and distal tempestites
MFS
Fort Mountain Formation
0 m
mudstone
vf f m c vc
sandstone
cgl.
B
Lake Oesa
Peyto Formation
575 m
FS/SB
Carbonate ramp
Shallow-subtidal sand sheets
Inner-shelf – shallow-subtidal compound-dune fields
Wiwaxy Peaks Member
Inner-shelf sand-ridge complex
MFS
FS/SB
Shallow-subtidal sand sheets
Shallow-subtidal compound-dune fields
Moraine Lake Member
Inner-shelf compound-dune fields and tempestites
MFS
FS/SB
Shoreface
Compound dunes
25 m
MFS
Prodelta-like
FS
FS/SB
Shoreface
Lake Oesa Member
0 m
RSME
Intertidal
mudstone
vf f m c vc
sandstone
cgl.
Legend
Trough cross-stratification
Planar cross-stratification
Hummocky cross-stratification
Lenticular bedding
Ripple cross-lamination
Low-angle cross-stratification
Paleocurrent direction
Pipe rock with *Skolithos linearis*
High ichodiversity of horizontal trace fossils of arthropods and worm-like organisms
Convolute bedding

Figure 5

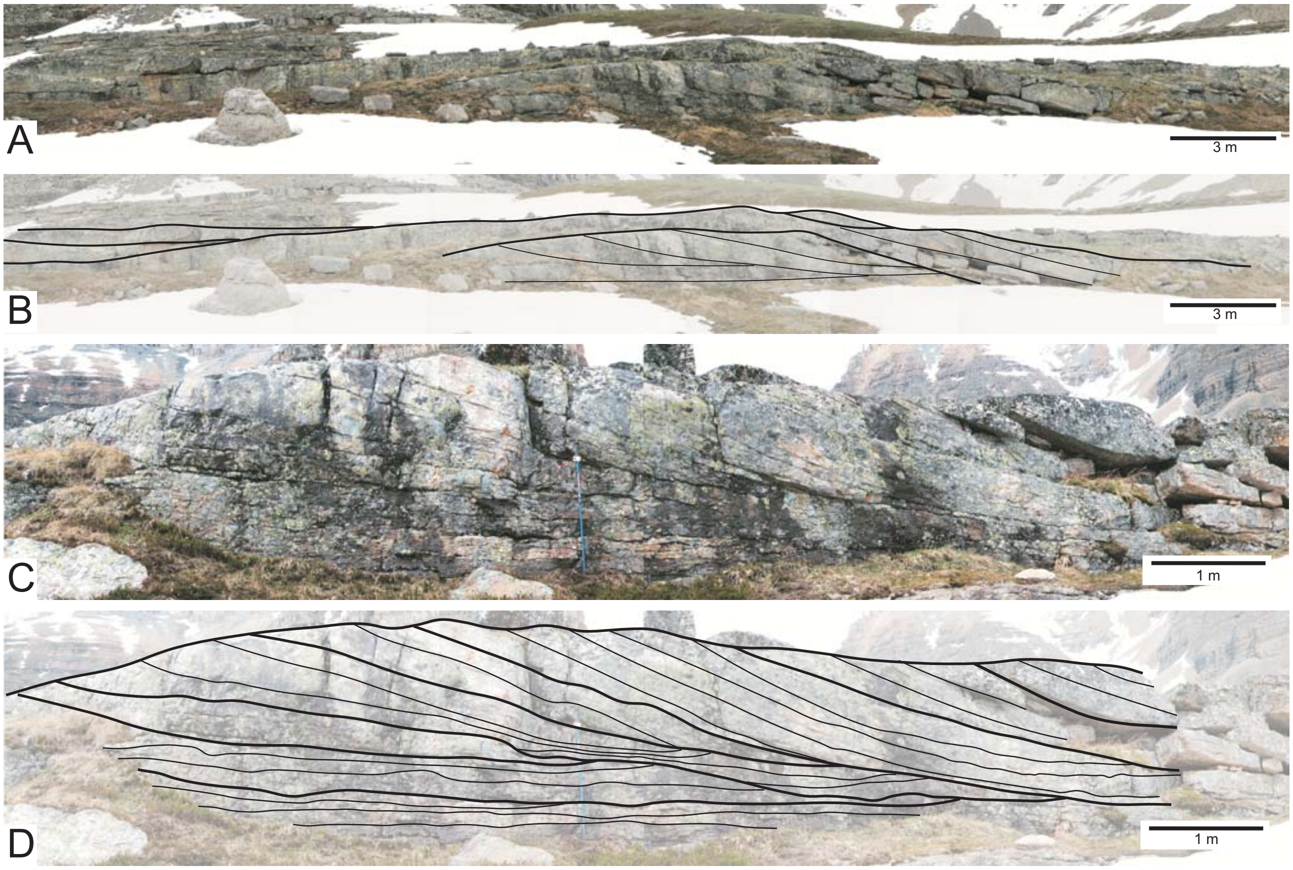


Figure 6

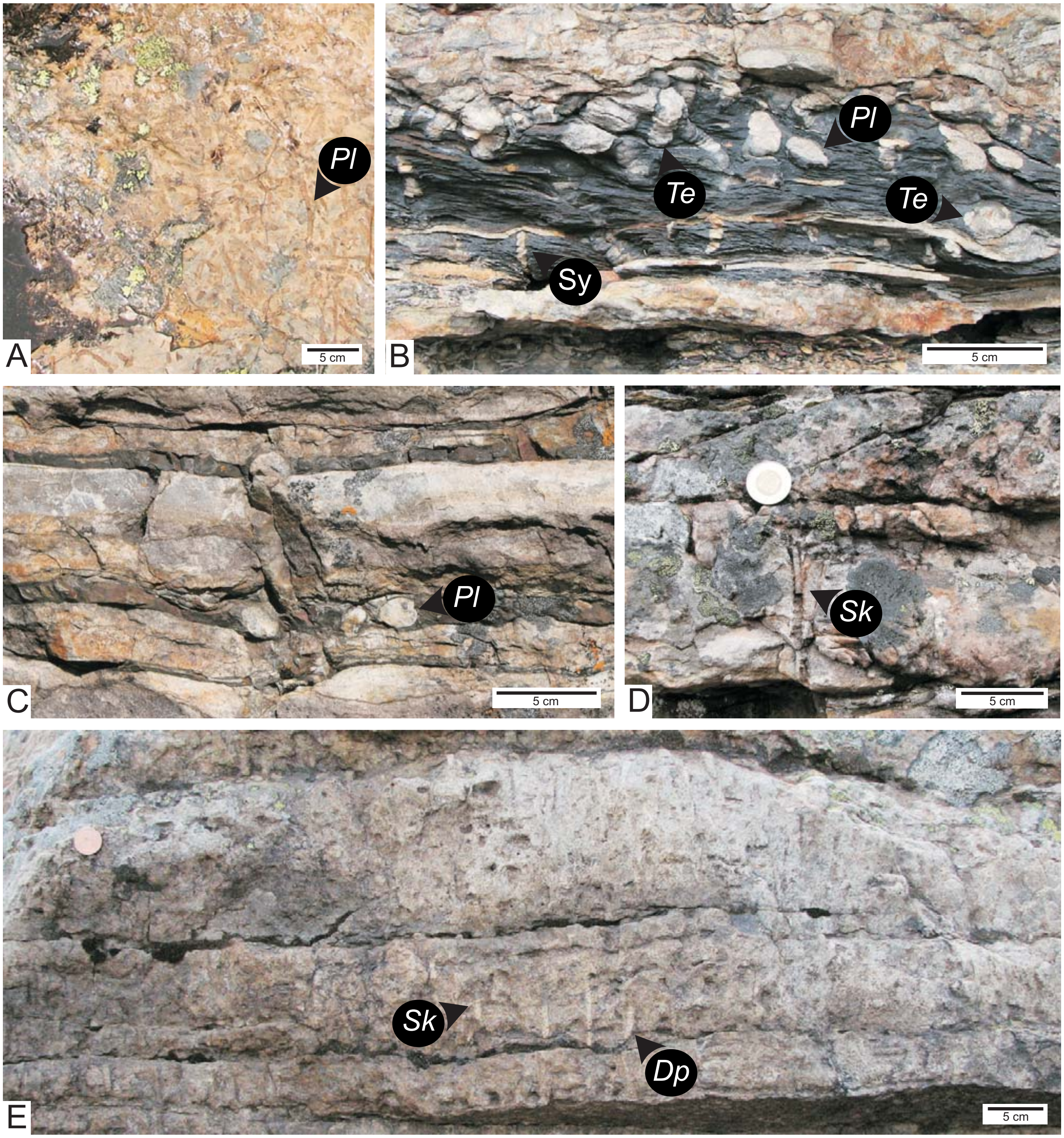


Figure 7

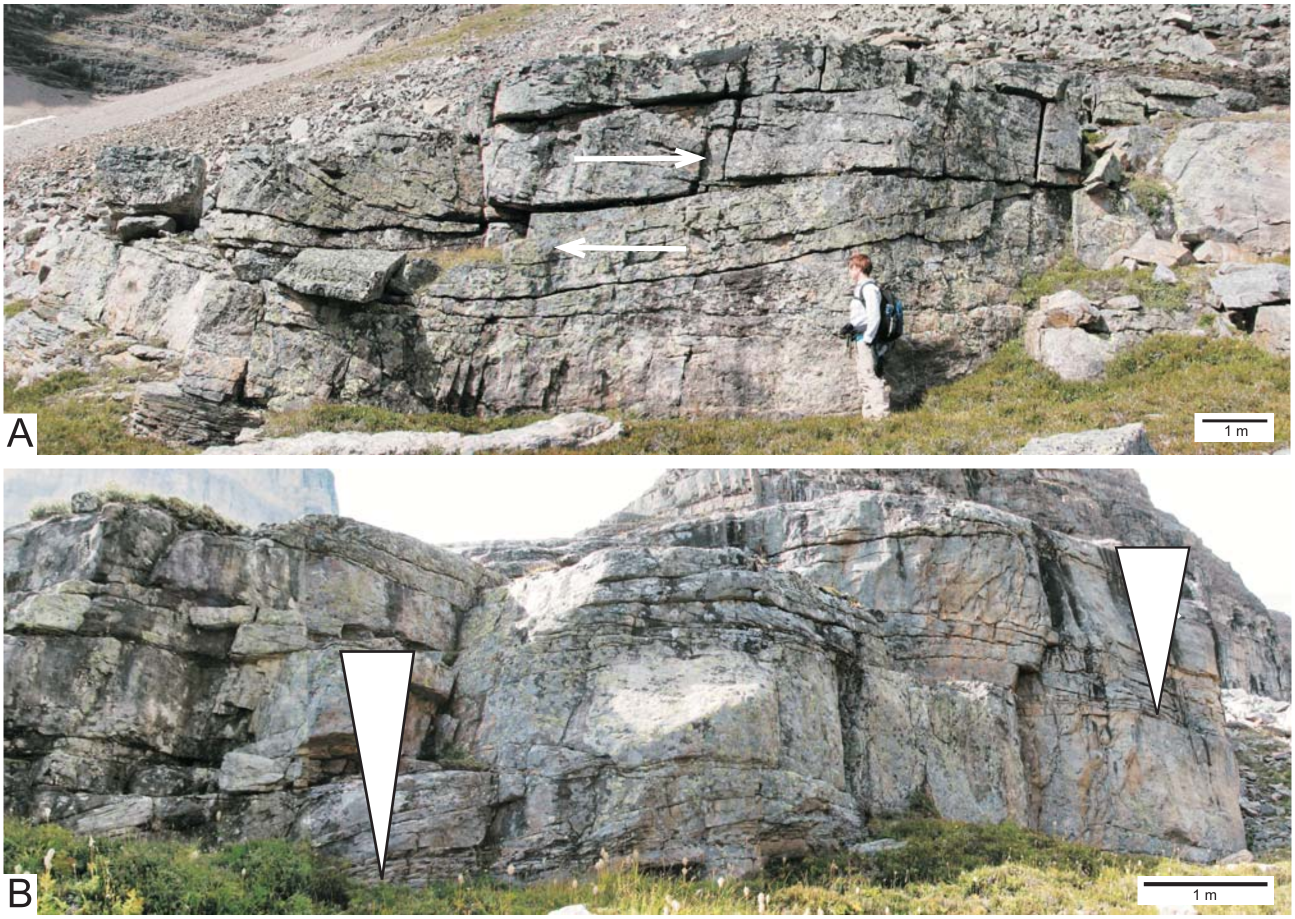


Figure 8

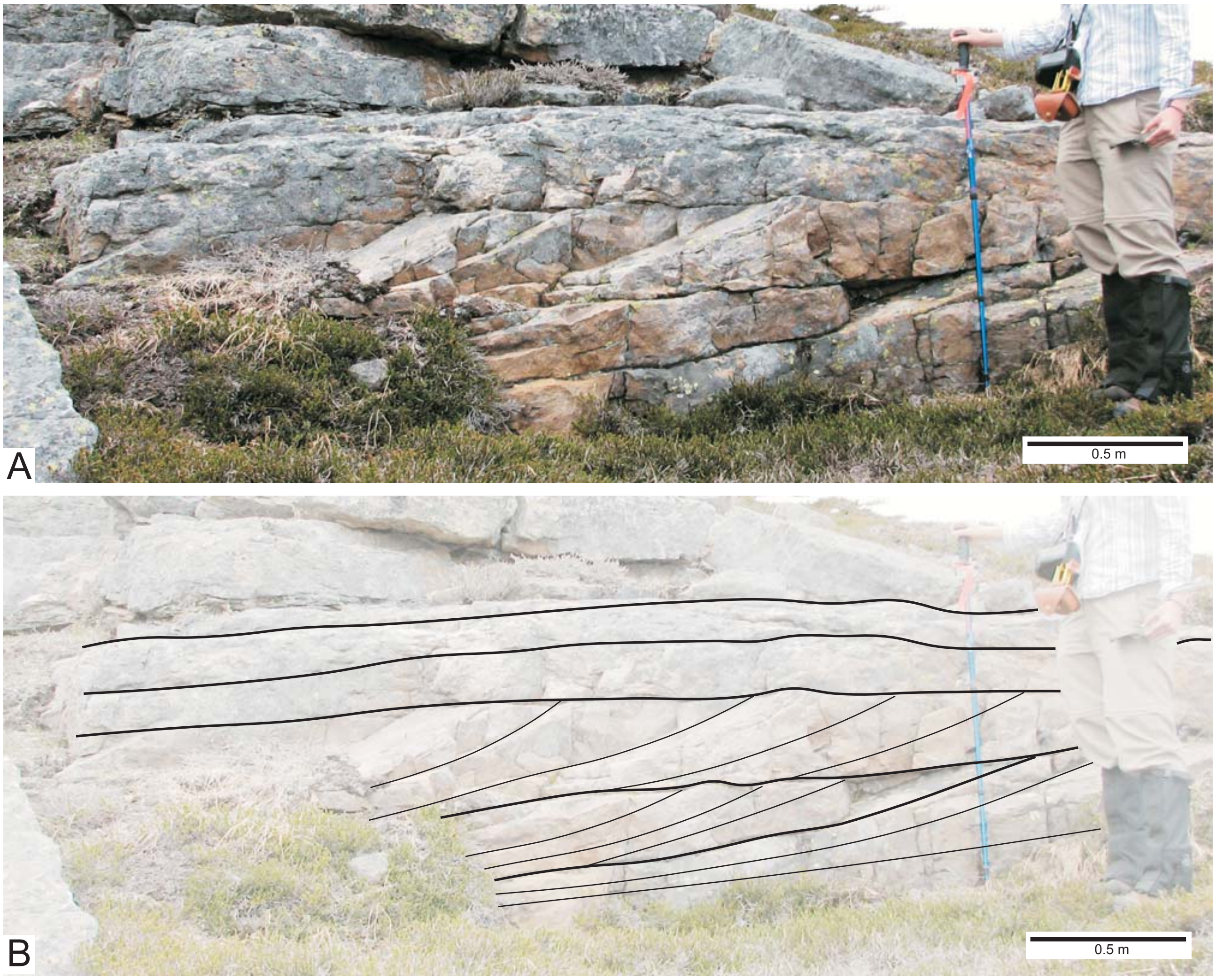


Figure 9

Figure 10

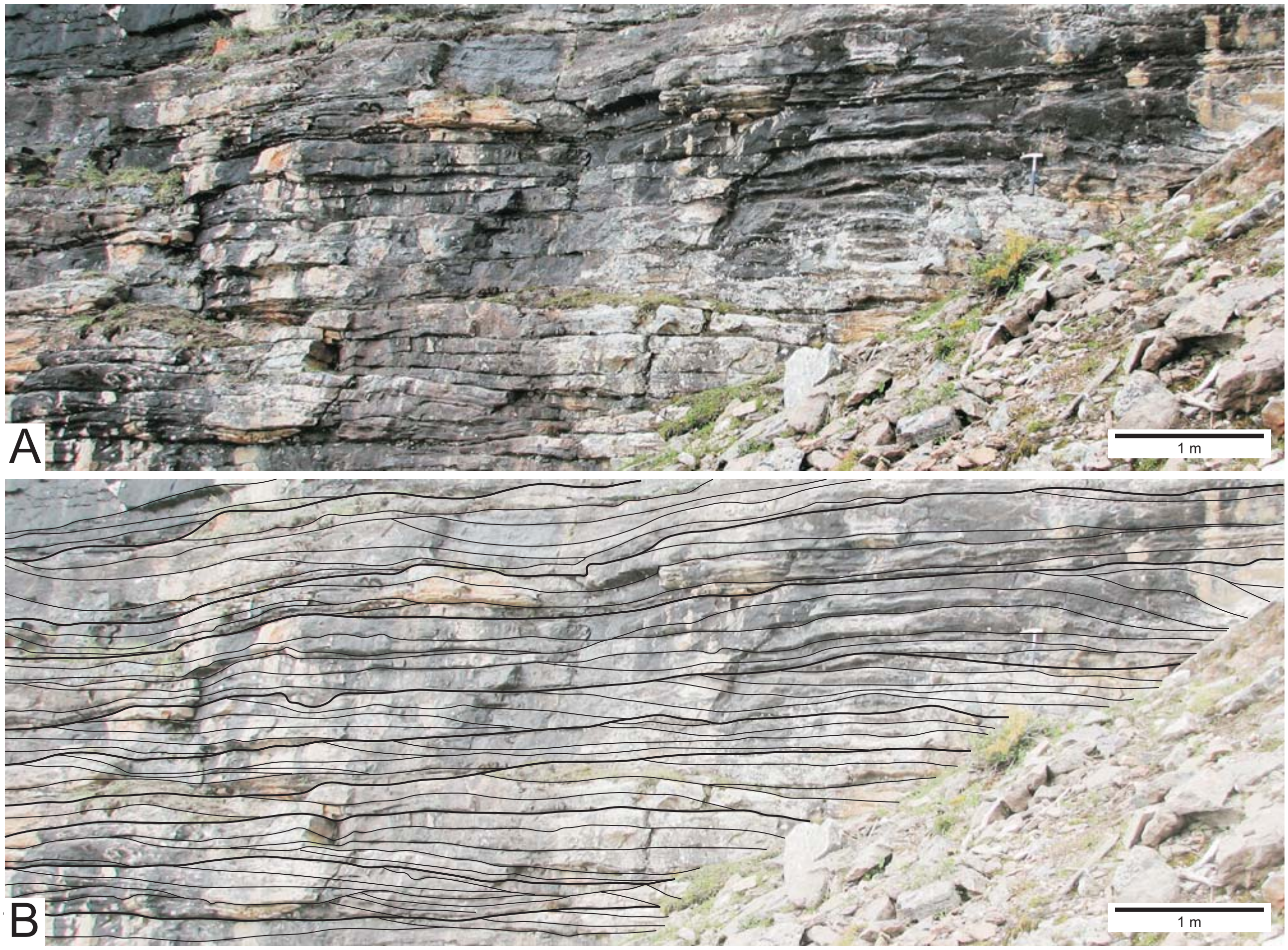


Figure 11

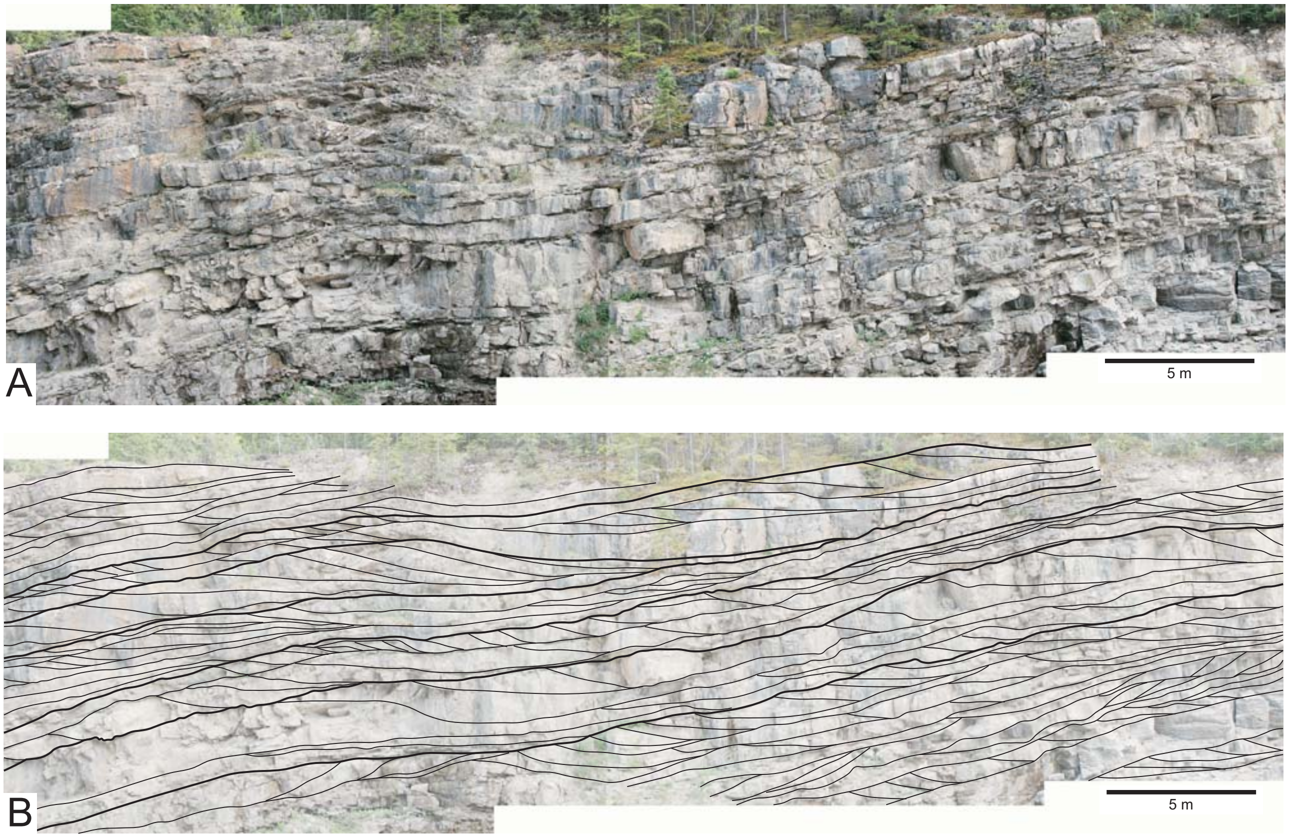


Figure 12

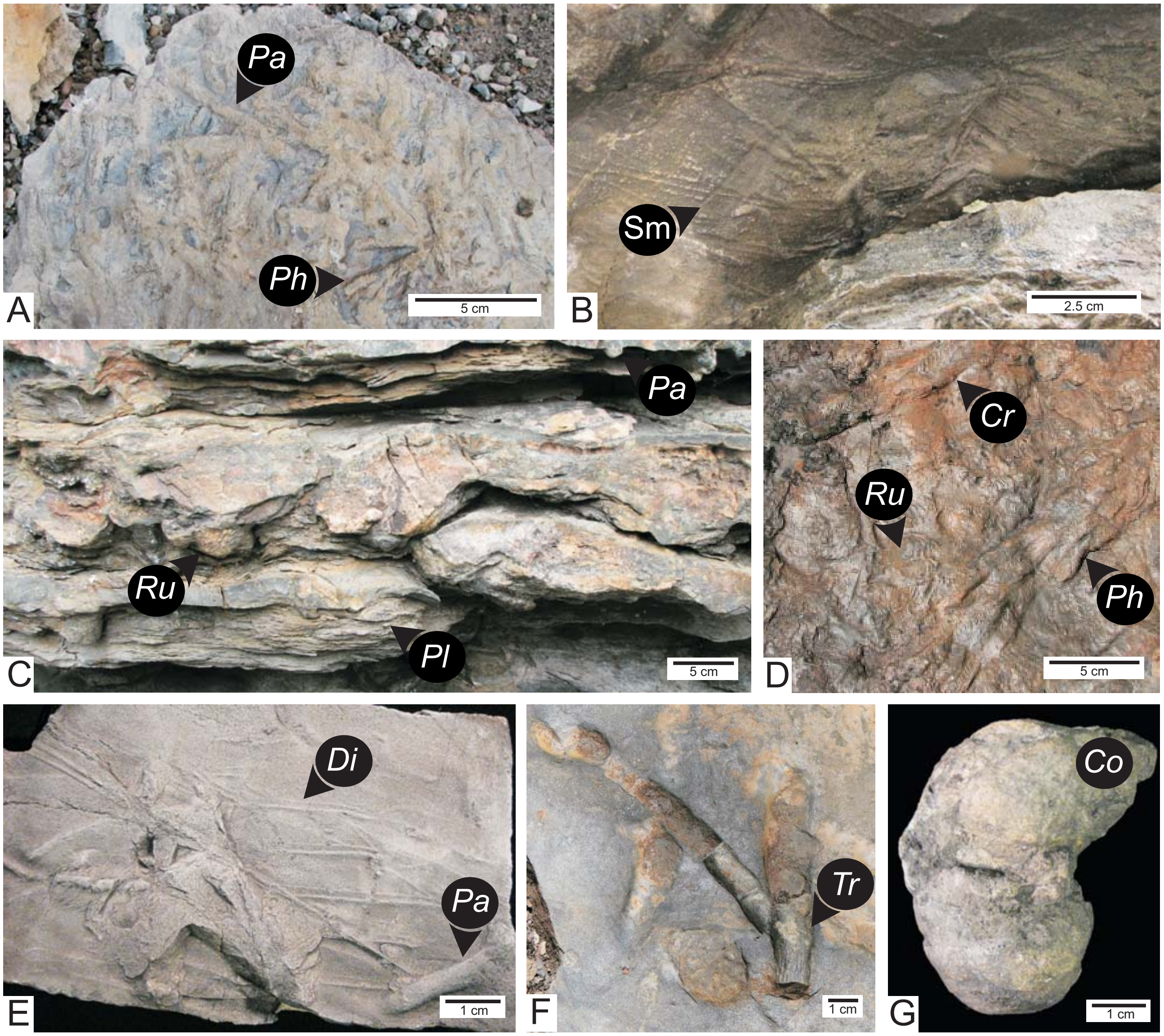

Pa
Ph
5 cm
A
Sm
2.5 cm
B
Pa
Ru
Pl
5 cm
C
Cr
Ru
Ph
5 cm
D
Di
Pa
1 cm
E
Tr
1 cm
F
Co
1 cm
G

Figure 13

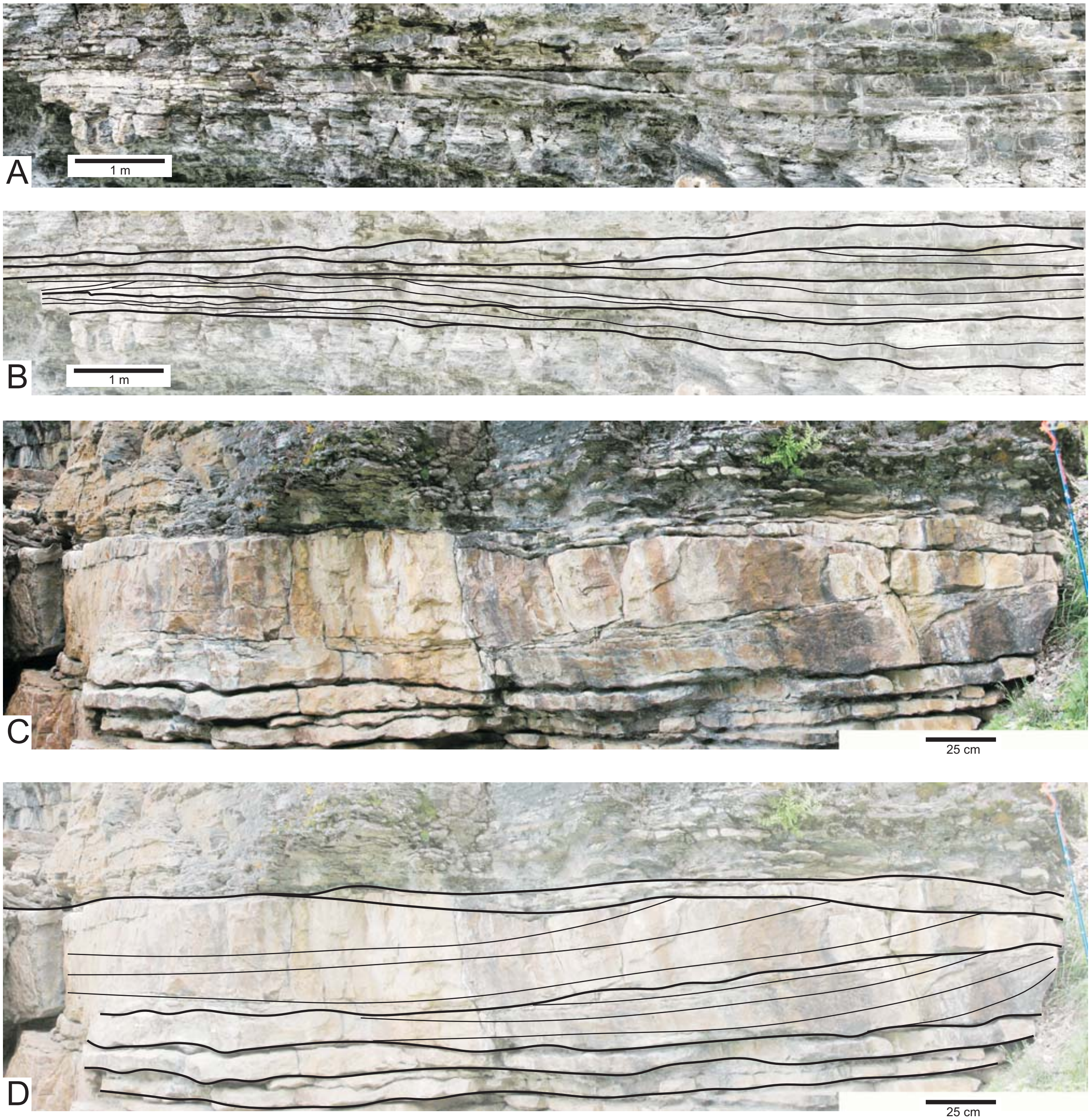


Figure 14

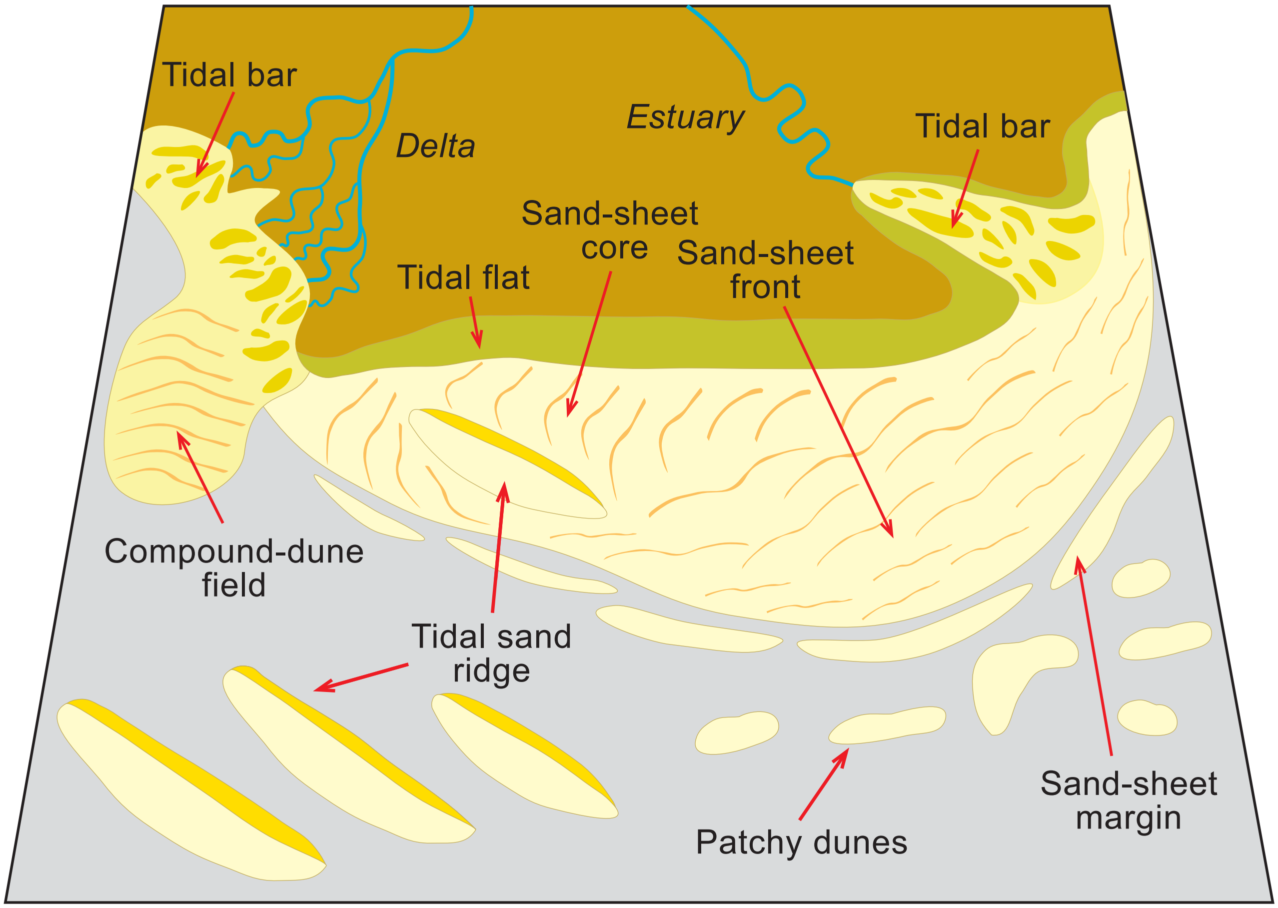

Tidal bar
Delta
Estuary
Tidal bar
Sand-sheet core
Sand-sheet front
Tidal flat
Compound-dune field
Tidal sand ridge
Patchy dunes
Sand-sheet margin

Figure 15

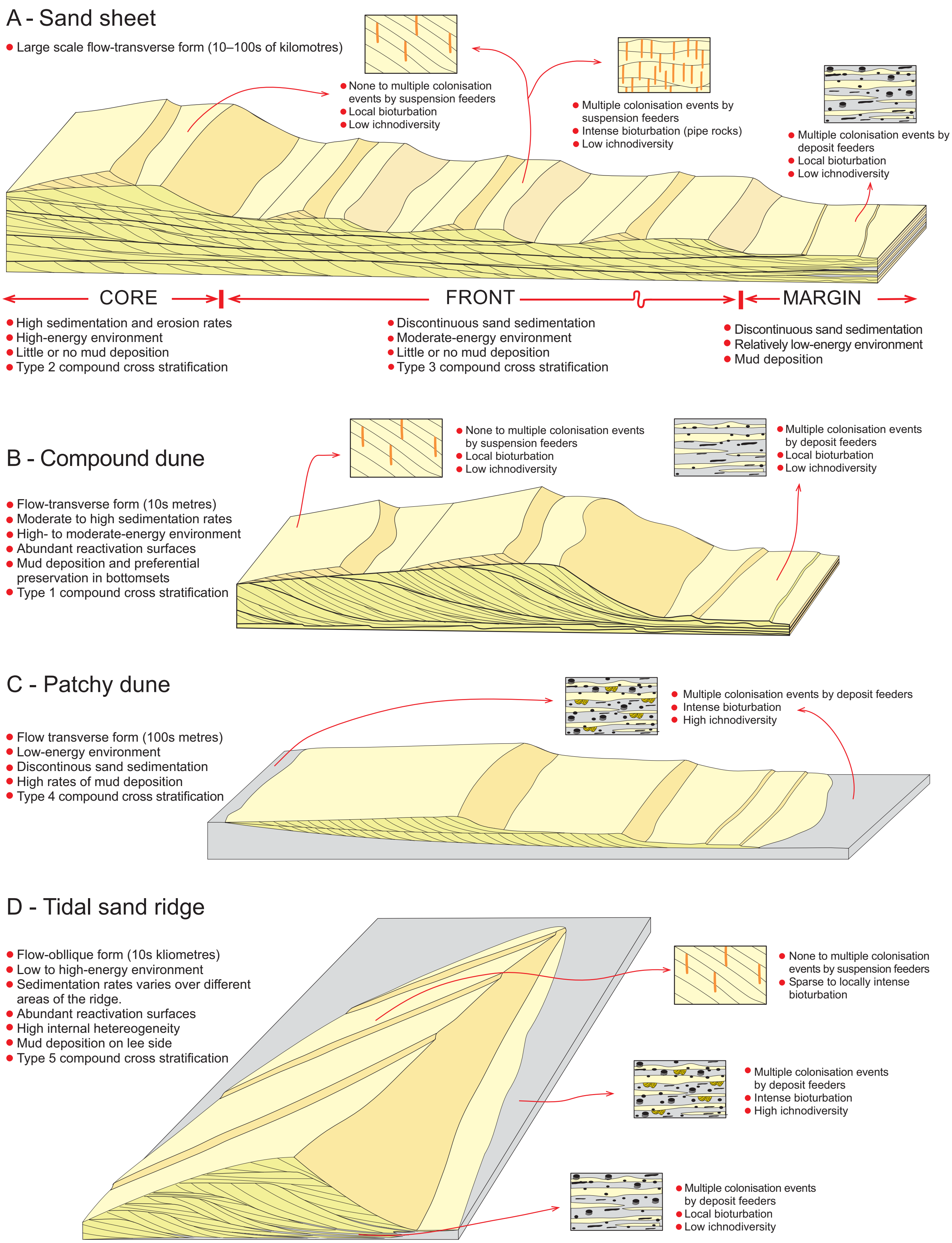

A - Sand sheet
Large scale flow-transverse form (10–100s of kilomotres)
None to multiple colonisation events by suspension feeders
Local bioturbation
Low ichnodiversity
Multiple colonisation events by suspension feeders
Intense bioturbation (pipe rocks)
Low ichnodiversity
Multiple colonisation events by deposit feeders
Local bioturbation
Low ichnodiversity
CORE
FRONT
MARGIN
High sedimentation and erosion rates
High-energy environment
Little or no mud deposition
Type 2 compound cross stratification
Discontinuous sand sedimentation
Moderate-energy environment
Little or no mud deposition
Type 3 compound cross stratification
Discontinuous sand sedimentation
Relatively low-energy environment
Mud deposition
B - Compound dune
None to multiple colonisation events by suspension feeders
Local bioturbation
Low ichnodiversity
Multiple colonisation events by deposit feeders
Local bioturbation
Low ichnodiversity
Flow-transverse form (10s metres)
Moderate to high sedimentation rates
High- to moderate-energy environment
Abundant reactivation surfaces
Mud deposition and preferential preservation in bottomsets
Type 1 compound cross stratification
C - Patchy dune
Multiple colonisation events by deposit feeders
Intense bioturbation
High ichnodiversity
Flow transverse form (100s metres)
Low-energy environment
Discontinous sand sedimentation
High rates of mud deposition
Type 4 compound cross stratification
D - Tidal sand ridge
Flow-obllique form (10s kliometres)
Low to high-energy environment
Sedimentation rates varies over different areas of the ridge.
Abundant reactivation surfaces
High internal hetereogeneity
Mud deposition on lee side
Type 5 compound cross stratification
None to multiple colonisation events by suspension feeders
Sparse to locally intense bioturbation
Multiple colonisation events by deposit feeders
Intense bioturbation
High ichnodiversity
Multiple colonisation events by deposit feeders
Local bioturbation
Low ichnodiversity

Figure 16